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THE SORPTION OF SULFUR DIOXIDE IN A CYCLED COLUMN: A COMPARISON STUDY

William D. Morgan

Pennsylvania State University

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Center for Air Environment Studies
The Pennsylvania State University

THE SORPTION OF SULFUR DIOXIDE IN A CYCLED COLUMN: A COMPARISON STUDY

William D. Morgan

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Project Director

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continued on inside back cover

The Pennsylvania State Univeristy

The Graduate School

Department of Chemical Engineering

The Sorption of Sulfur Dioxide in a Cycled Column: A Comparison Study

A thesis in

Chemical Engineering

by

William D. Morgan

Submitted in partial fulfillment
of the requirements
for the degree of

Master of Science

March 1970

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I. SUMMARY

A method for scrubbing SO_2 from air has been tried and proven moderately successful. A liquid suspension of carbon and water was used as the liquid in a controlled cycle column.

The experiments were performed with a basic one sieve plate column. Analysis of the outgoing vapor stream was done by bubbling it through a hydrogen peroxide solution and titrating the resultant sulfuric acid with a standard solution of sodium hydroxide.

The major objective of this study was to compare the overall efficiencies obtained under a variety of conditions. The column was operated continuously and cycled. The liquid was either plain water or the carbon-water suspension. During the various runs, the following conditions were varied: the mass flow rate of gas, the liquid cycle time, the vapor cycle time, the liquid rate (for continuous runs), and the inlet concentration of SO_2.

The best overall efficiencies were obtained when the column was cycled using the carbon-water suspension. A liquid cycle time that allowed all the liquid on the plate to be replaced for each cycle, and low mass flow rates of gas also gave high efficiencies. The inlet concentration of SO_2 and the efficiency were found to be independent of each other.

II. INTRODUCTION

Ridding the air of foul smelling, corrosive, and sometimes deadly gases has pushed man to developing many elaborate schemes. The majority of these are based on sound chemical engineering principles, but due to economics, they are rarely used. One of the most basic ways of cleansing the air is by scrubbing it in a column with either an absorbent such as water, or an adsorbent such as carbon.

Basically, gas purification can be broken down into four categories:

1. Gas absorption by a liquid (water)
2. Gas adsorption by a solid (carbon)
3. Chemical conversion (catalytic oxidation)
4. Special specific methods (condensation)

Each technique has its own good and bad points. In absorption, the liquid is easily handled, but it has a relatively low capacity. The adsorption technique offers a relatively high capacity, but solids are usually very difficult to handle. The chemical conversion technique has a high capacity and fairly easy handling if a liquid is involved. However, the liquid can be corrosive and there are costs due to solvent losses and the replacement of the chemical used in the reaction.

Due to the inherent difficulties of both absorption

and adsorption methods, they were combined into one process. The result was a technique known as sorption. This method uses a suspension of the solid adsorbent in the liquid absorbent. Recent studies have been carried out by Mehta (11) and Quach (18) with a sorption medium of carbon in water. In general, the sorption technique combined the high capacity of the adsorbent with the ease of handling of the absorbent.

Carbon and water were chosen as a adsorbent and absorbent respectively for several reasons. Both are very inexpensive. The activated carbon has extremely good adsorbing qualities while the water offered itself as the ideal absorbent. The activated carbon used was Nuchar 190-C.

In 1964, Robinson (19) did work on the use of cycling to enhance the operation of a sieve plate column. The results of Robinson's work show that the efficiency can be substantially increased if the column is cycled. The operation of a cycled column takes place in two distinct stages. First, with liquid on the plate, the gas is allowed to pass through the sieve plate and the liquid. Then, the gas flow is stopped, and the liquid is allowed to drain from the plate. At the same time, the liquid on the plate is replenished with fresh liquid. Usually, the vapor flows approximately 80% of the total cycle time, and the time for a total cycle is from two to twenty seconds. The longer cycle time and the complete separation between

the liquid and vapor flow periods, differenciates cycled operation from pulsed operation.

It has been shown that cycling and sorption used separately will improve the efficiency of a column (11,18,19). The mechanisms by which these processes increase the efficiency are relatively simple. The sorption process has basically the following mechanism:

1. The SO_2 gas diffuses through the bulk gas phase, through the gas film, to the gas-liquid interface.
2. After going through the interface, the SO_2 diffuses through the liquid film and into the bulk liquid phase.
3. The SO_2 then diffuses through the liquid film surrounding the carbon particle to the surface of the carbon.
4. It is then adsorbed into the pore structure of the carbon.

A pictoral diagram of this process is shown in Figure 1. Qualitatively, sorption frees the SO_2 from the water, leaving the water free to absorb more SO_2. The driving force for getting the SO_2 through the liquid film is therefore maintained at a high level.

Cycling produces an enhanced efficiency due to the non-linear relationship between the driving force and time. When the column is operated continuously, an average driving force exists at steady state. During

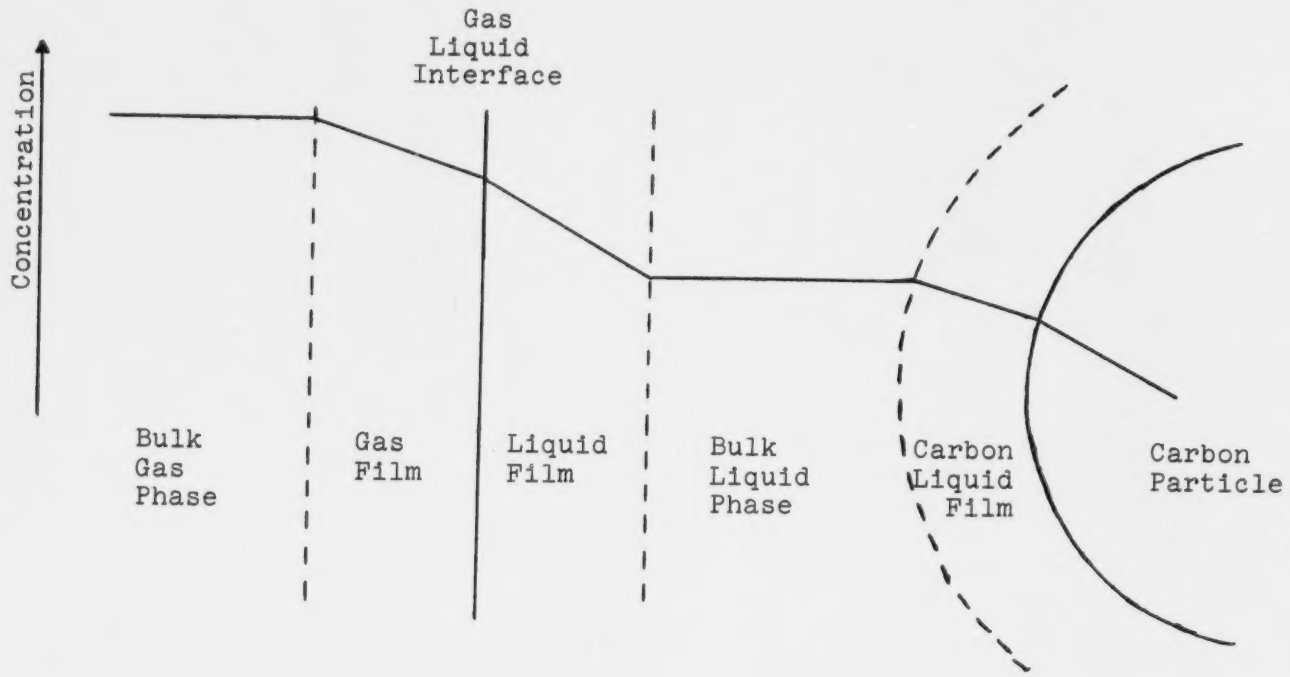

Figure 1.

A Pictoral Representation of Concentration Gradients

in a Sorption System

cycled operation, the column is at unsteady state conditions. At the start of the cycle, the driving force is great. As the cycle progresses, the driving force tapers downward in a non-linear fashion. The average value of the driving force obtained by integrating the values of the driving force over the entire cycle is higher than the average value of the driving force during an equivalent continuous run. There may also be an increase in the value of K, the overall mass transfer coefficient, due to some mass transfer taking place during the liquid flow period of the cycle. Robinson found this to be true in his study of cycling (19). This may be true in this case also, but to a fairly small degree. Most of the SO_2 was absorbed in the liquid on the plate. When the liquid flow period started, very little SO_2 was left in the gas space to be absorbed.

Historically speaking, a large body of literature exists dealing with absorption and adsorption as separate studies, yet relatively little work has been done with the combined process of sorption. One of the first works in the area was carried out by Findlay (3) in 1910. In this study, Findlay and Creighton came to the conclusion that a suspension in water will not necessarily increase the solubility of the gas, but is dependent on the gas and suspension used. In their specific experiments with nitrous oxide and a charcoal suspension, the solubility of the gas was greatly increased over the solubility in plain

water.

Between the work of Findlay and Creighton in 1910, and 1951, very little work was done in the area of sorption. After 1951, several articles were written (12,15,16,17,20) on the study of sorption. Most of this work originated in Hungary and dealy mainly with the understanding of catalytic reactions. More recently, the U.S. Public Health Service has carried out a number of studies (6,7,13,14) on the use of activated carbon in the treatment of waste water. No prior work was found dealing with the sorption of SO_2 using a carbon and water suspension.

The concept of using controlled cycling as a method of mass transfer was first proposed by Dr. M.R. Cannon in 1952 (2). From 1952 to 1964, several papers were wtitten on the subject, especially as it concerns distillation and extraction (1,4,9). The papers showed tray efficiencies of well over 100% and even as high as 200%. No real explanation for these extraordinarily high efficiencies could be found until McWhirter's work in 1962 (8,10). McWhirter produced a computer simulation of a cycled column and showed that the efficiencies could approach 200% in some cases. In 1964, Robinson (19) further explained the theory behind cycled column operation.

III. STATEMENT OF THE PROBLEM

This study was carried out to gain information on the sorption of SO_2 in a cycled column. Comparatively, how much better or worse is the efficiency in a sorption column versus a column using plain water? Does cycling with a carbon and water suspension increase the efficiency over cycling with plain water? What effects do the inlet concentration of SO_2, the gas mass flow rate, the liquid flow rate, the vapor cycle time, and fraction of the liquid on the plate replenished per cycle, have on the efficiencies? How does cycling compare with continuous operation?

IV. PROCEDURE OF THE INVESTIGATION

A schematic diagram of the apparatus is shown in Figure 2. The liquid supply tank was a steel quarter-barrel with the top cut off. It was painted on the inside with Tygon paint to retard rusting. An agitator was used in the tank when runs were being made with the carbon-water suspension. For runs made with water, tap water was used. For the carbon-water runs, a suspension of 0.1% (weight basis) carbon was mixed in the tank.

The liquid was pumped out of the tank to either a small or large calibrated rotameter. A three-way valve controlled the direction of flow. The smaller rotameter was used for continuous runs while the large rotameter was used for cycled runs.

The liquid entered the column by a downcomer when continuous runs were in progress or through a shower cap assembly when cycled runs were being made. Both the downcomer and the shower cap were made of 316 stainless steel. Figures 3 and 4 show the column as it appears for continuous and cycled runs respectively. A detailed drawing of the shower cap appears in Figure 5. The shower cap is built so as to simulate a plate above the column. It has the same number, same size, and same arrangement of holes as the sieve plate.

The liquid exited from the column by way of an 1/8-

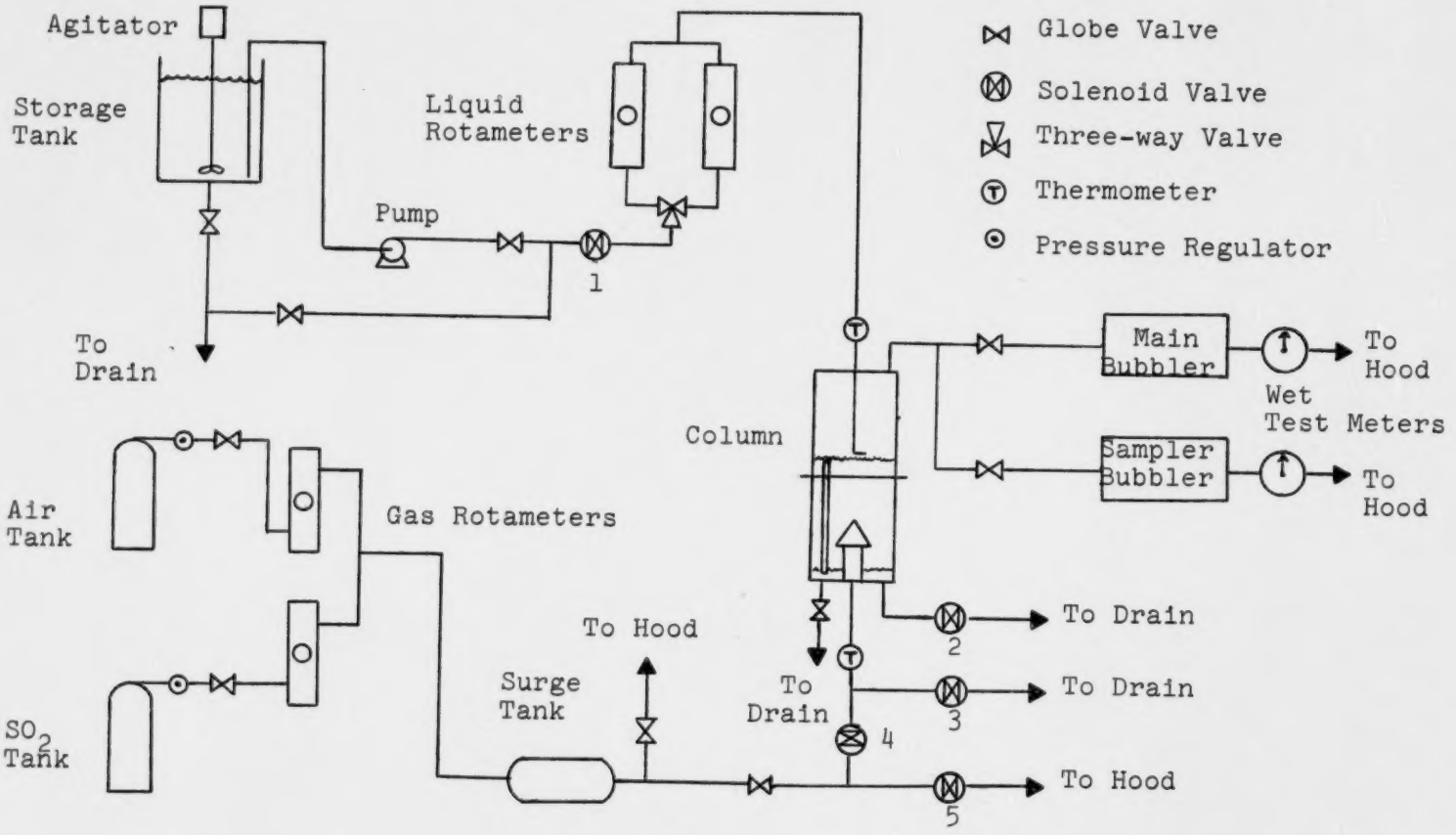

Figure 2.

Equipment Schematic Diagram

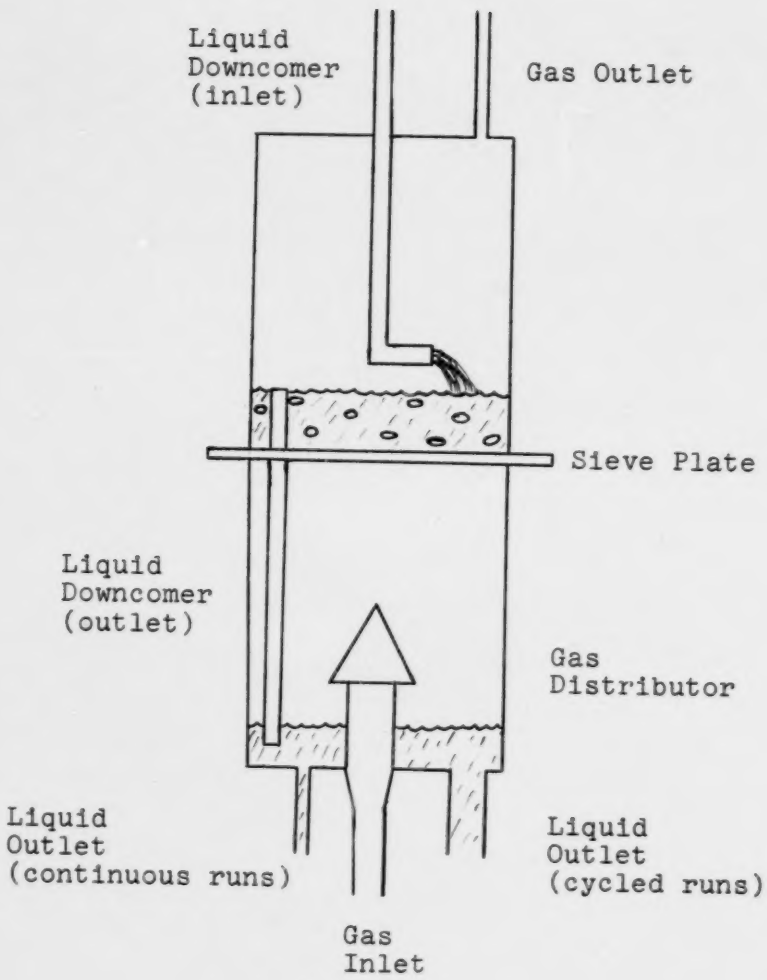

Figure 3.

Column Configuration for Continuous Runs

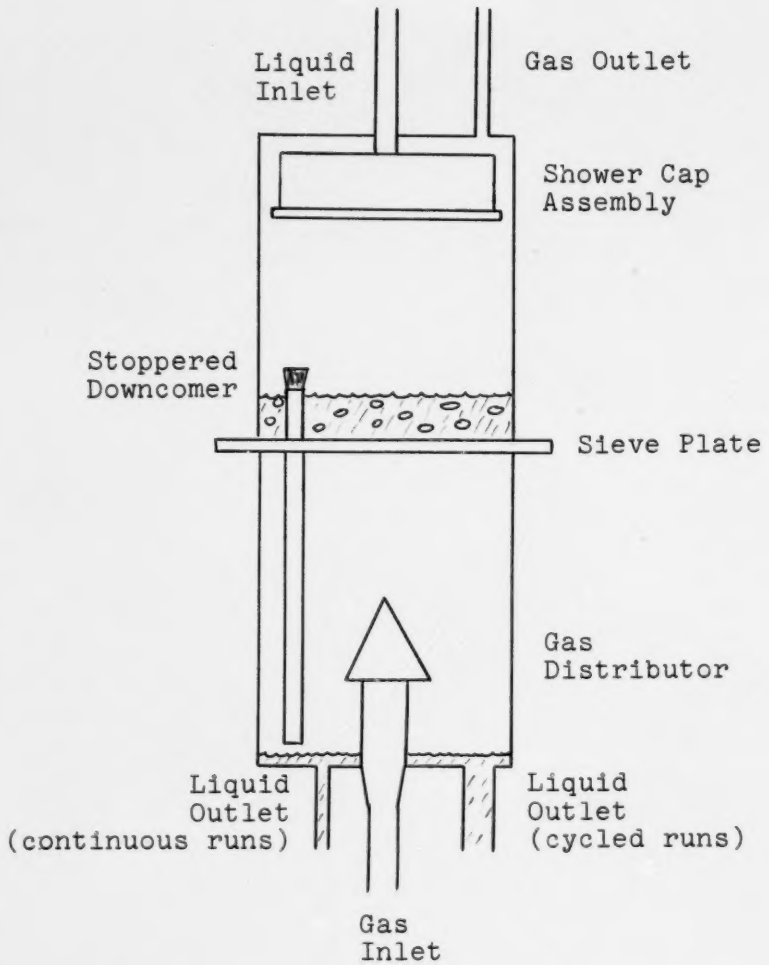

Figure 4.

Column Configuration for Cycled Runs

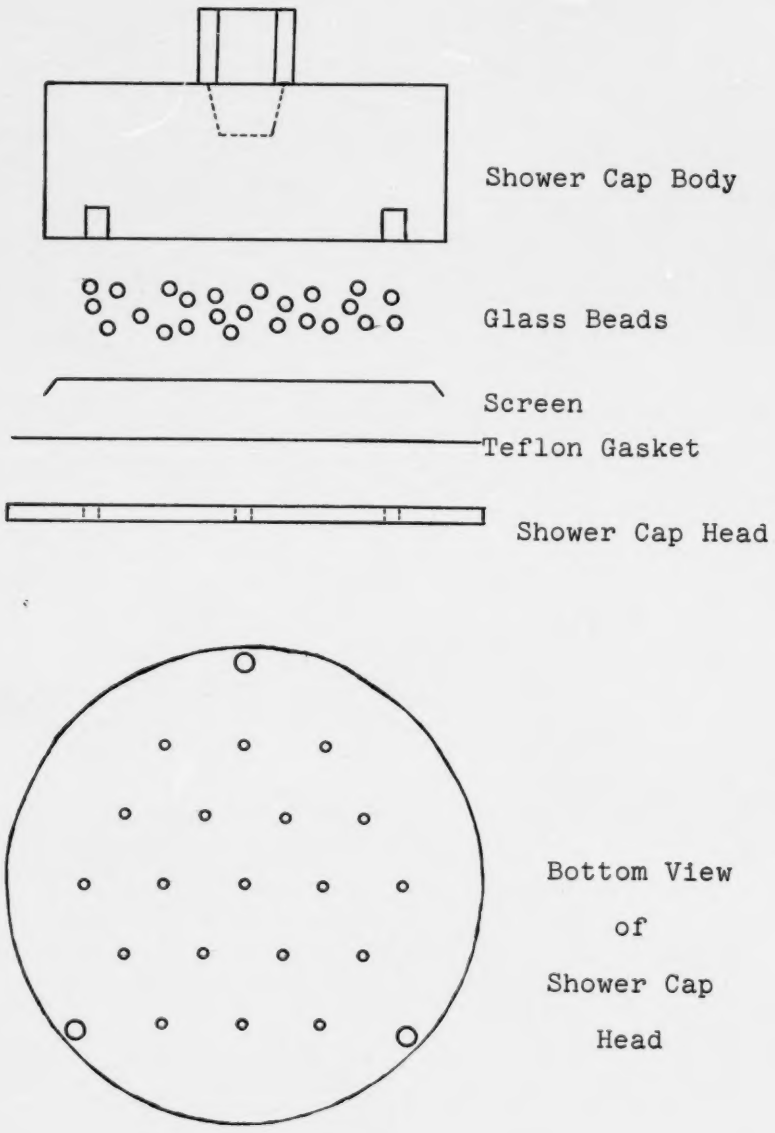

Figure 5.

Shower Cap Assembly

inch mild steel drain tube and valve if the run was continuous, or through a 1/2-inch mild steel piping and a solenoid valve if the column was being cycled. The liquid was not analyzed and was passed directly to the drain.

The sieve plate employed was made of 1/4-inch 316 stainless steel. It has nineteen sieve holes, each 1/16-inch in diameter arranged on a 7/8-inch triangular pitch. A 1/2-inch stainless steel tube was located near the edge of the column and was used as a downcomer. It extended approximately 1 1/2 inches above the sieve plate and ended approximately 1/2-inch from the bottom of the column. During cycled runs, this downcomer was stoppered. The column itself was made of two 4-inch inside diameter Pyrex pipe sections. Teflon gaskets were used, and all mild steel that came into contact with the SO_2 was painted with Tygon paint to inhibit corrosion. All piping and fittings which came into contact with SO_2 gas were either stainless steel or Teflon.

Sampling of the exit gas stream was accomplished by bubbling part of the main gas flow through a series of bubblers and a wet test meter. The bubblers contained 75 milliliters of a dilute hydrogen peroxide solution. The SO_2 in the sample stream was scrubbed and reacted with the hydrogen peroxide to form sulfuric acid. The resulting acid solution was then titrated using a standardized sodium hydroxide solution. The final result of the analysis was the average concentration of

SO_2 in the exit gas stream. Full details on this procedure may be found in the booklet published by the U.S. Department of Health, Education, and Welfare (5). The gas inlet stream composition was assumed to be constant and was preset for a run using calibrated rotameters on the SO_2 and air.

Three mixtures of SO_2 and air were produced in the laboratory by mixing pure SO_2 and dry air from compressed gas cylinders. A mixing tee and a stainless steel surge tank allowed the gas mixture to become thoroughly mixed. Mixtures of 4%,5%, and 6% SO_2 in air by volume were used in the various runs.

After the surge tank, the gas went through a series of solenoid valves to a gas ditributor in the base of the column. The vapor bypass control valve (5 on Figure 2) was used to bypass the gas during the liquid cycle of cycled operation. This allowed the gas to be prepared continuously and reduced surges into the column. It also kept relatively high pressures off the solenoid valves. If the valves were subjected to more than 8 psi, the diaphragm would break and the valve would have to be replaced. The vent valve (3 on Figure 2) for the gas was necessary in order to reduce the pressure in the bottom section of the column during the liquid flow period. This allowed the liquid to drain freely from the plate.

For continuous runs, the main liquid inlet valve (1 on Figure 2) was left continuously open, while the

vapor vent valve (3 on Figure 2), and the main liquid outlet valve (2 on Figure 2) were closed. The main gas inlet valve (4 on Figure 2) was also left continuously open. The liquid was allowed to drain from the column by a small manual valve.

During cycled operation, the soleniod valves were opened and closed by a Flexopulse timer. During the liquid flow period, the main gas inlet valve was closed, while all others were open. When the vapor flow started, the system reversed itself.

The action of the solenoid valves was controlled from a panel of toggle switches. Figure 6 shows the layout of the control box.

The following data were collected for each run:

1. inlet concentration of SO_2 Y_i
2. outlet concentration of SO_2 Y_o
3. gas flow rate V
4. liquid flow rate L
5. vapor and liquid cycle times t_{vc} and t_{lc}
6. vapor and liquid temperatures T_v and T_l

A quantity phi (Φ) was also calculated and used as a variable during cycled runs. Phi is the fraction of the liquid that is replaced during the liquid flow period. That is, if phi equaled one, all the liquid on the plate was removed and fresh liquid replaced on the plate. If phi equaled one-half, then only one-half of the liquid was replaced.

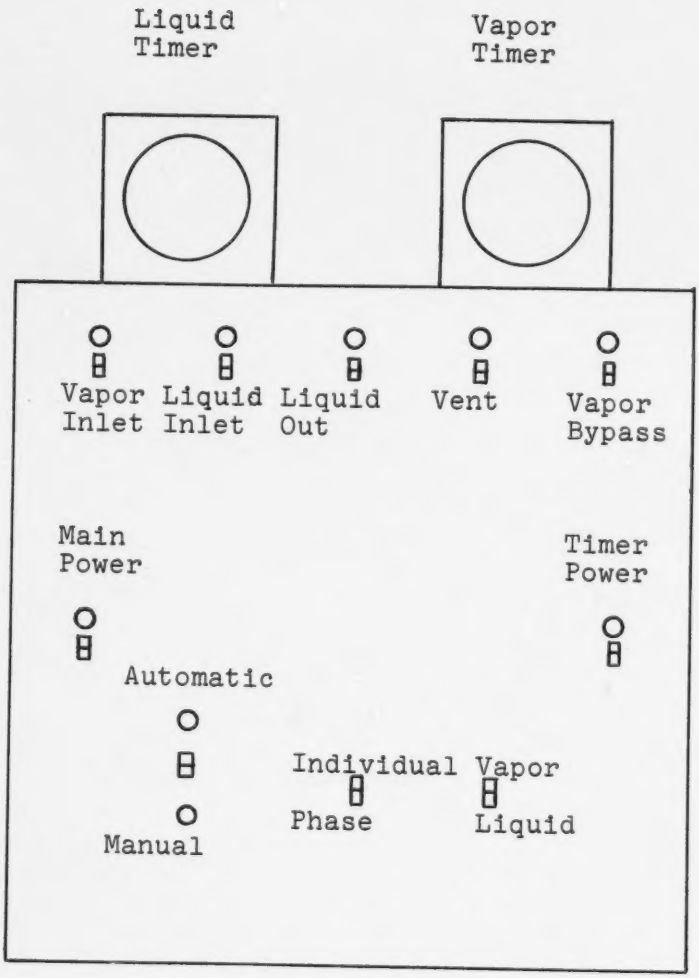

Figure 6.

Control Box Layout

Efficiencies were calculated on a weight bases.

$$\text{Efficiency} = \frac{S_i - S_o}{S_i} \times 100 \qquad (1)$$

where Efficiency = percent

S_i = SO_2 into column, grams/minute

S_o = SO_2 out of column, grams/minute

For comparison, the gas mass flow rate, G $\frac{lb}{hr.\ ft.^2}$ was plotted against the efficiency. The rate of absorption, J grams/minute, was also plotted against G. The derivation of S_i, S_o, and G can be found in Appendix A.

V. RESULTS AND DISCUSSION

Continuous Runs

The results of the continuous runs are shown graphically in Figure 7 and Figure 8. Figure 7 shows the relationship between the total mass flux and the gas mass flow rate. Figure 8 is a plot of the gas mass flow rate versus the overall efficiency.

Using the basic two film theory, the rate of absorption may be written in two forms:

$$J = dN/dt = k_l a\ (x^* - x) \qquad (1)$$

$$J = dN/dt = k_g a\ (y - y^*) \qquad (2)$$

Equation 1 represents the rate of absorption through the liquid film while equation 2 represents the rate of absorption through the gas film.

Values for k_l and k_g may be based on penetration theory. Penetration theory differs from the two film theory in that the two film theory assumes a steady-state absorption rate. The penetration theory assumes that the rate of absorption is time dependent. Based on penetration theory, the following theoretical equations for k_g amd k_l may be derived:

$$k_g = (2/RT_{vi})\ (D_g/\pi t_g)^{1/2} \qquad (3)$$

$$k_l = 2(D_l/\pi t_l)^{1/2} \qquad (4)$$

All experimental correlations for k_g and k_l for sieve

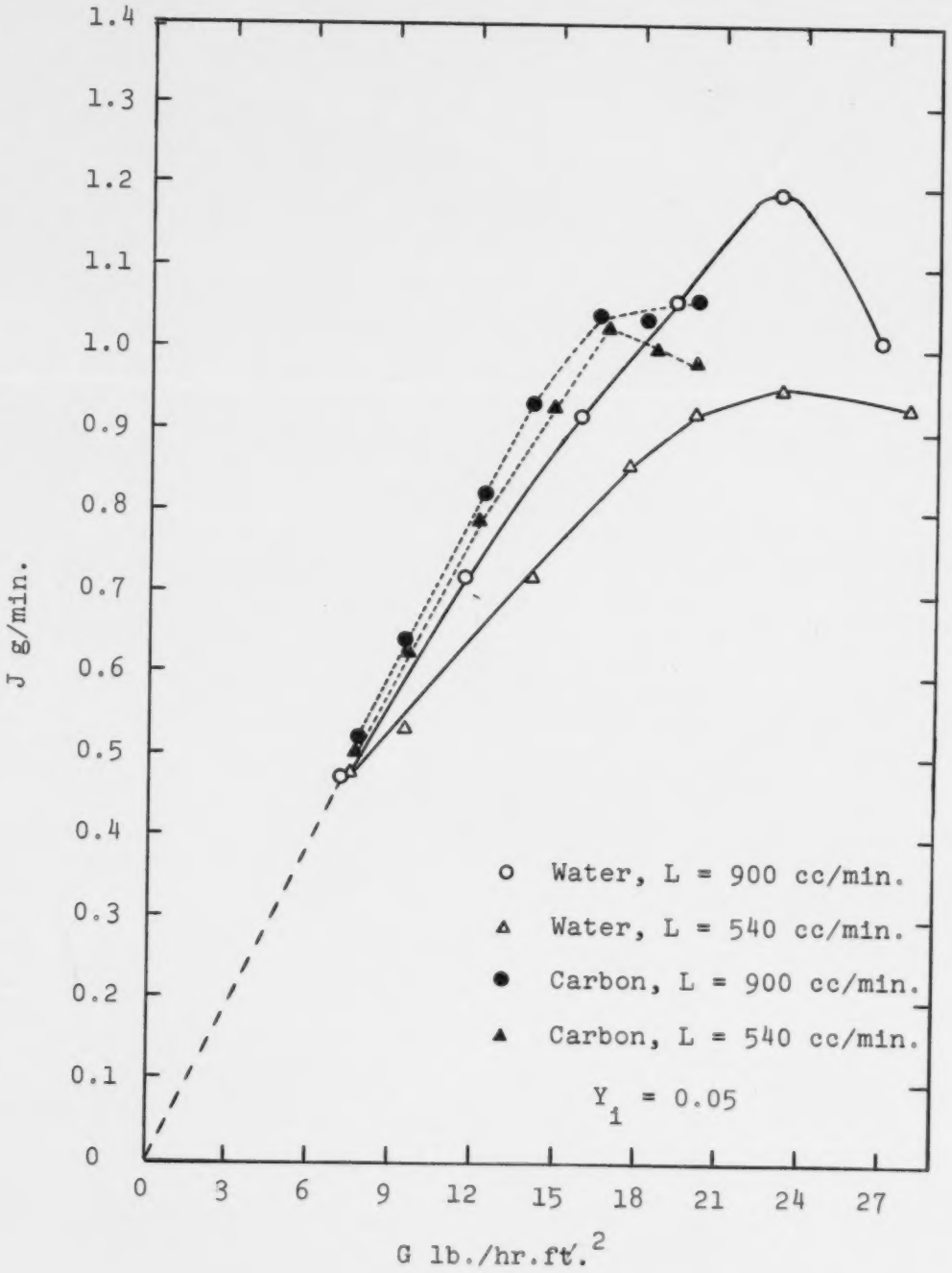

Figure 7.

Continuous Runs
J versus G

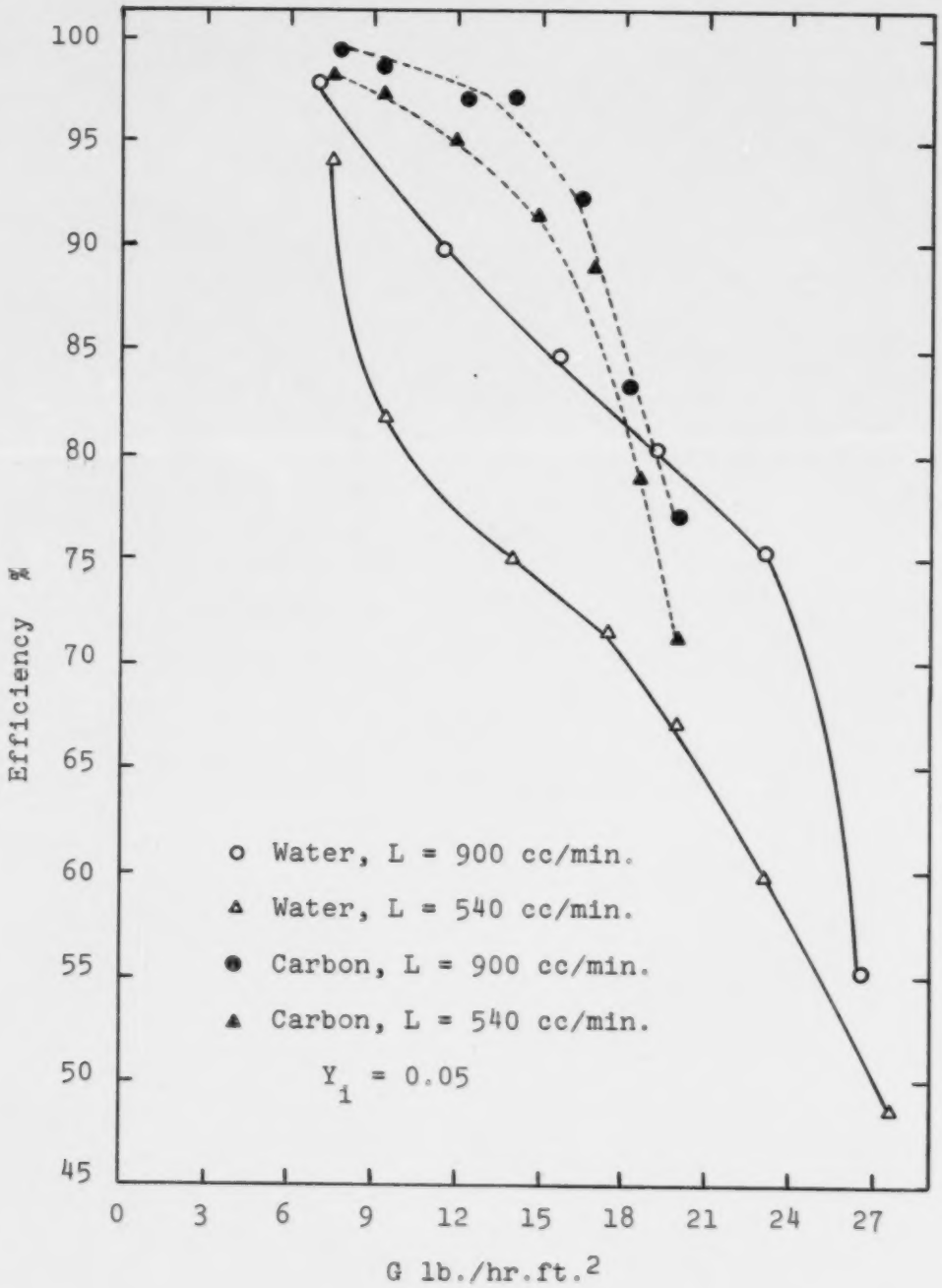

Figure 8.

Continuous Runs
Efficiency versus G

plates are merely further refinements of the two basic equations. No correlations for a sieve plate resulting in k_g or k_l could be found in the literature. The following two expressions for k_g and k_l are presented by Whitney and Vivian (21) and are for SO_2 at 30^0C. in a packed column. A packed column has a discontinuous liquid phase and a continuous gas phase. A sieve plate column has a continuous liquid phase and a discontinuous gas phase. As such, the following correlations should not be used to calculate values of k_g and k_l, but should be used in a comparative sense only.

$$k_l = .152G_l^{.82} \qquad (5)$$

$$k_g = .028G^{.7}\, G_l^{.25} \qquad (6)$$

The system of SO_2 - water tends to be a liquid phase controlling system. This is due mainly to the limited solubility of SO_2 in water. The important equation is therefore equation 1. Because the gas is only slightly soluble in water, the gas phase has relatively little trouble keeping the interface saturated with SO_2. The rate of transfer therefore depends on how rapidly the liquid can remove the material from the interface.

Several interesting phenomena can be noted from Figure 7. A lower liquid flow rate results in a lower mass flux. The lower liquid flow rate results in a longer contact time between the liquid and the gas, t_l. If t_l increases in Equation 4, k_l must decrease, considering D_l as a constant. The equilibrium mole

fraction, x* is derived from the following equation:

$$P = Hx^* \qquad (7)$$

Henry's Law constant,H, and the partial pressure of SO_2, P, are not dependent on the liquid flow rate. The equilibrium mole fraction, x*, will therefore remain unchanged. Figure 7 also shows that for the two water runs, the decrease in the mass flux was approximately proportional to the decrease in the liquid rate. This means that the mole fraction of SO_2 in the liquid, x, is nearly constant. At low and moderately high gas flow rates, the mass fluxes tended to be closer together. This results in an increase in k_1 and a constant or possibly increasing value of x will result in an overall reduction in the mass flux. This hypothesis is based on Equation 1.

At high vapor flow rates, the mass flux goes through a maximum. The exact reason for this phenomenon cannot be explained with the data which is presented herein. The complication arises due to the multiple films which may exist in the gas-liquid-carbon system. The resistances from these films may interact in many ways to produce many effects. There are also several ways in which they may interact to produce the same overall effect.

Both Figures 7 and 8 show that the carbon in the water is increasing the efficiency of the column. The increase in the mass flux as indicated by Figure 7 also

indicated that the system is liquid phase controlled. If it were gas phase controlled, the use of carbon in the water would not change the mass flux. A small decrease in the mass flux is noted for a decrease in the liquid rate. This indicates that the carbon is taking some of the SO_2 out of the water, but not all of it.

Figure 7 also offers a paradox regarding the runs with carbon. If the runs become gas phase controlled at high vapor flow rates, all the data points at high gas flow rates should fall on the same line, regardless of whether there was carbon in the water or not. Instead, the carbon runs cross the water runs and become less efficient than the water runs. No clear explanation could be found for this phenomenon. Possible experimental error could have caused this to take place.

Most of this discussion has to do with the figures dealing with the mass flux due to its relationship with Equations 1 and 2. The figures depicting the efficiencies are also important. The efficiency and the mass flux are inter-related and the efficiency can sometimes give a slightly more realistic picture to just how much better one method of adsorption is over another method. It should be noted that at the high total efficiencies that were achieved, a small increase in efficiency has a significant effect on the amount of SO_2 that leaves the column. An increase from 98% to 99% in efficiency decreases the amount of SO_2 in the exit stream from

2% to 1%. This is a 100% relative decrease.

Cycled runs

Acomparison between the cycled runs and the continuous runs is shown in Figures 9 and 10. The efficiencies in Figure 10 are consistently better for the cycled runs. The cycled runs using the carbon-water suspension give the best efficiencies.

The mass flux as shown in Figure 9 does not have an apparent maximum for cycled runs. The cycled runs consistently have a higher mass flux than the continuous runs.

Effect of Phi (Φ)

Figures 11 and 12 show how the efficiency and the mass flux vary using phi (Φ) as a parameter. As phi

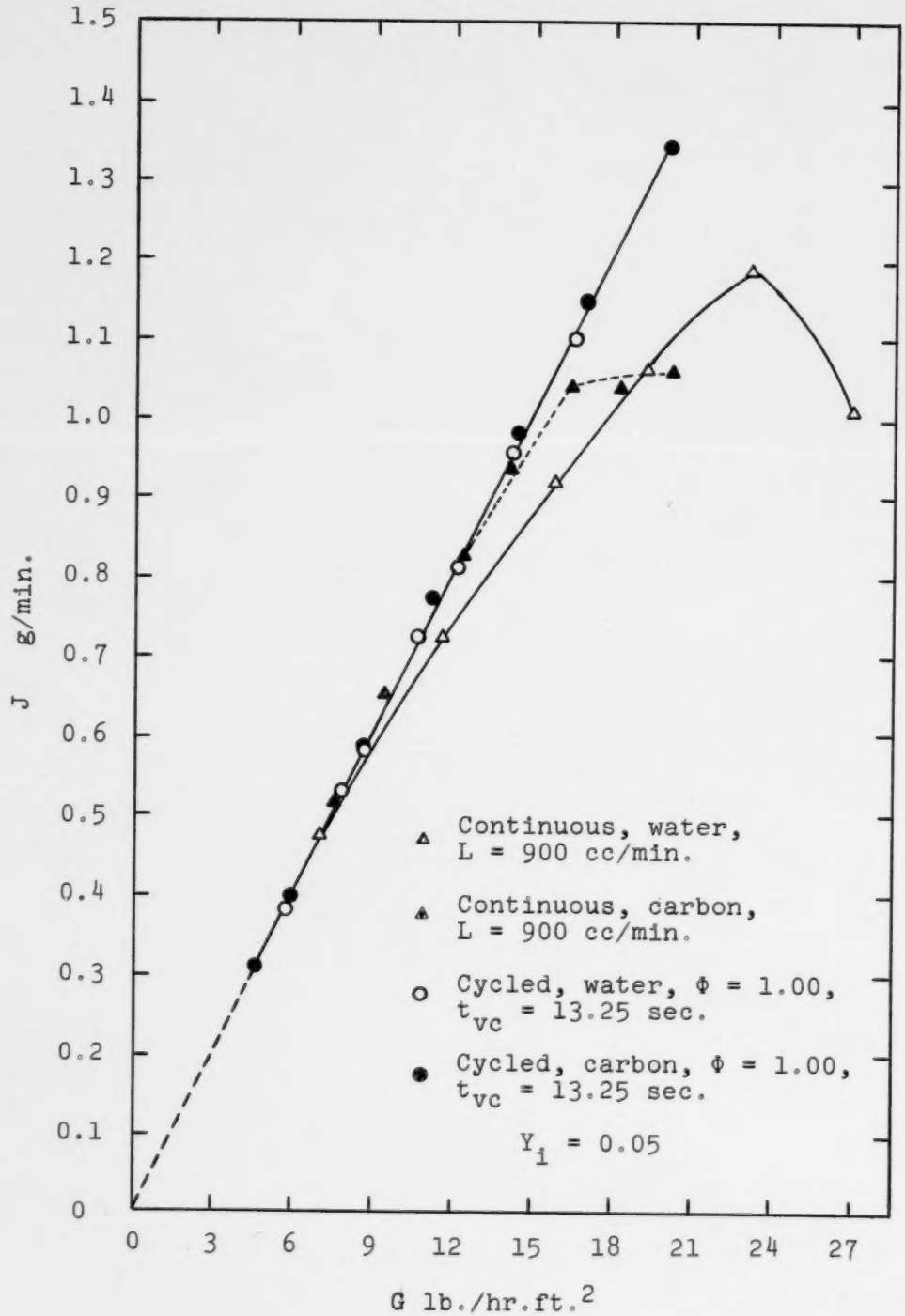

Figure 9.

Comparison of Continuous and Cycled Runs
J versus G

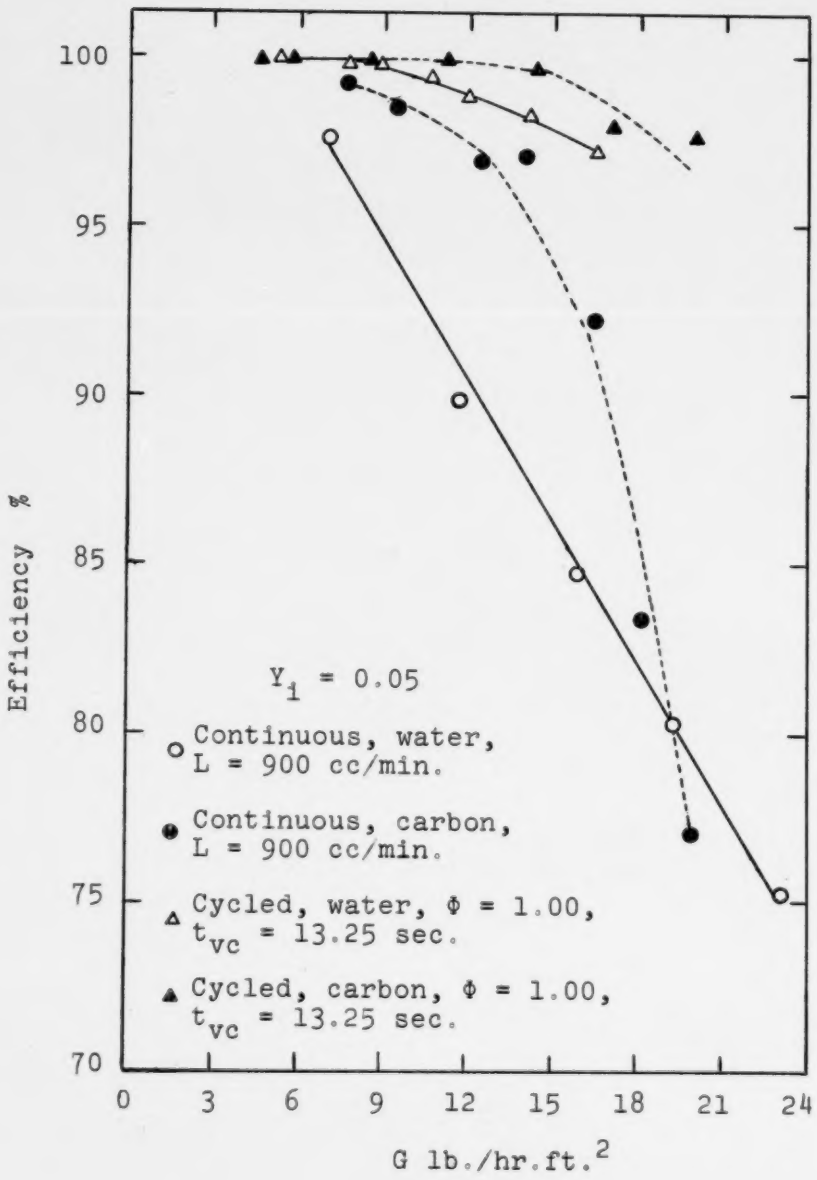

Figure 10.

Comparison of Continuous and Cycled Runs
Efficiency versus G

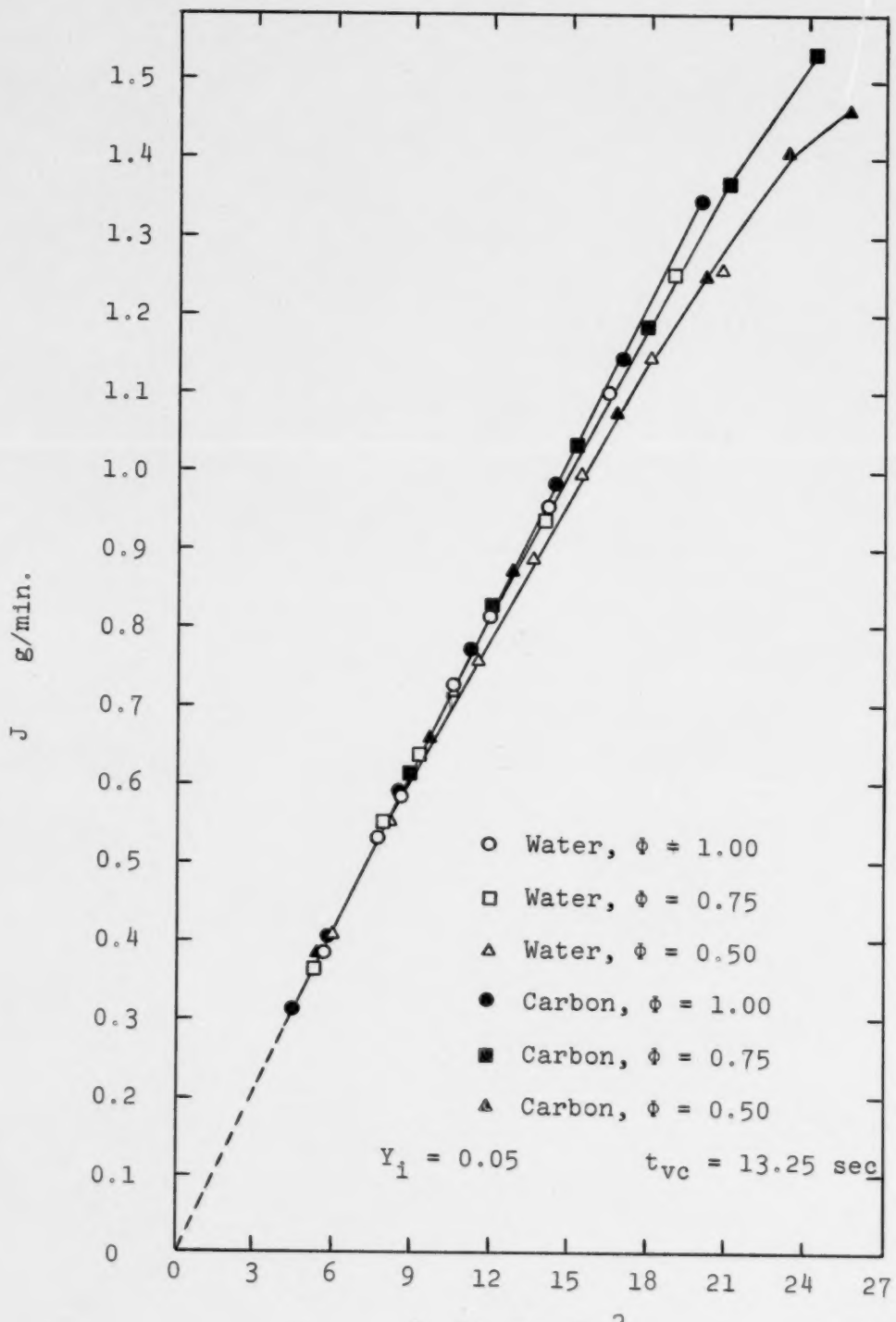

Figure 11.
Cycled Runs with Φ as Parameter

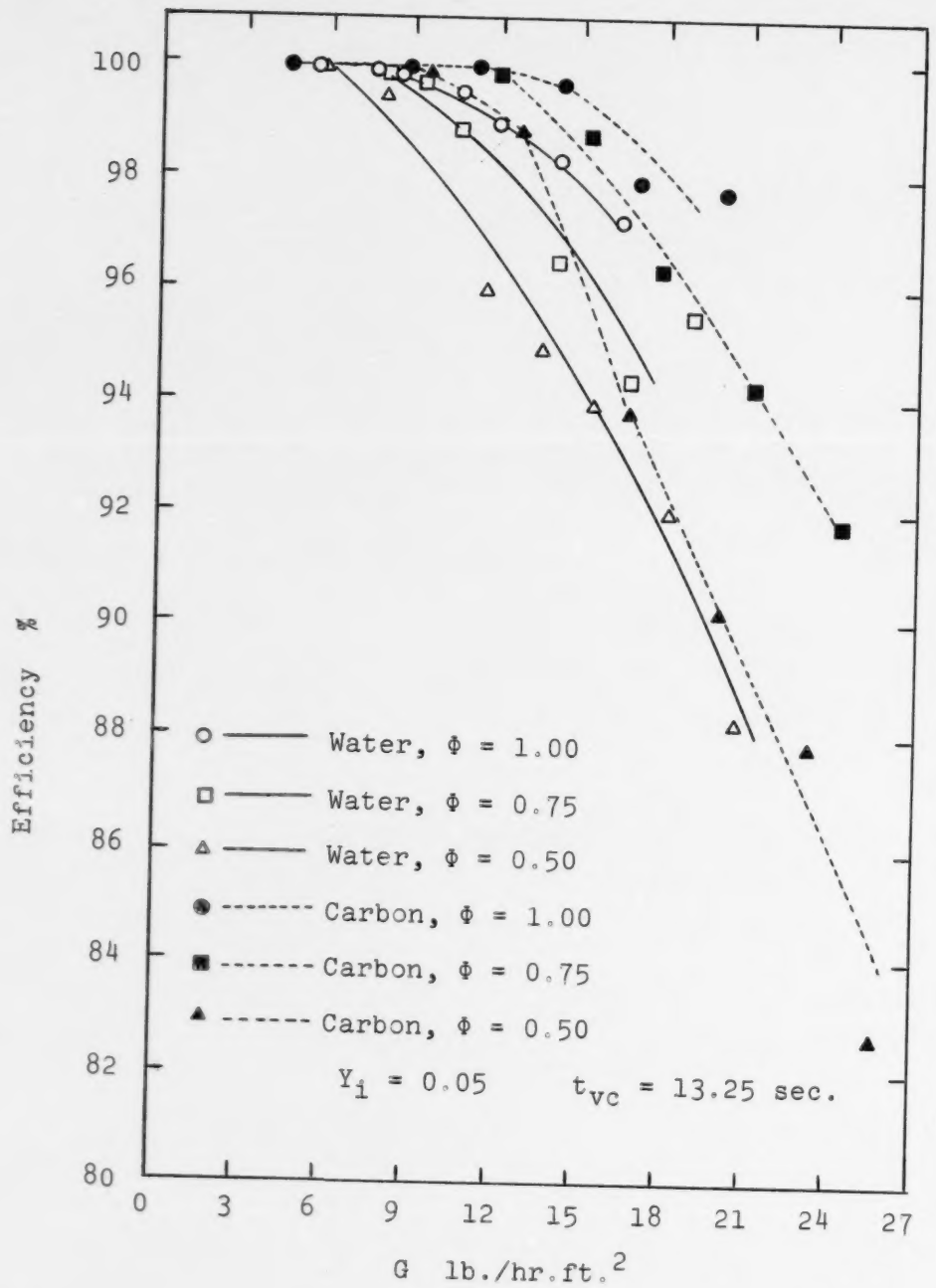

Figure 12.

Cycled Runs with Φ as Parameter
Efficiency versus G

decreases, the mass flux decreases, but only slightly. In the case of the carbon-water runs, the carbon did not seem to improve the absorption of the SO_2.

Due to the initially very high driving force, the system apparently became gas phase controlling. Usually the gas can keep the interface saturated, but due to the increased value of k_g because of the high driving force, the mass flux across the interface is greater than the gas can provide. The carbon in the liquid phase then becomes immaterial.

In actuality, the system is in a transition region at higher gas flow rates. If the system were strictly gas phase controlled, an alteration of phi would not give any change in the mass flux. This is true at low gas flow rates. As the gas flow rate increases, it is able to provide the SO_2 at the interface and the liquid becomes the significant resistance. At the higher gas flow rates the carbon should become more important due to the increasing importance of the liquid film. It is difficult to see any evidence of this happening from Figure 11. What is probably happening is that the carbon itself has a liquid film around it and an appreciable amount of SO_2 must accumulate in the bulk water phase before a sufficient driving force can overcome the resistance in the film. The accumulation of SO_2 in the water along with the fact that the liquid phase is of growing importance at high gas flow rates, would account

for the decrease in mass flux with the decrease in phi. As phi decreases, the initial concentration of SO_2 in the liquid increases. This causes a decrease in the overall driving force and a subsequent decrease in the mass flux.

Figure 12 shows that there is a slight increase in efficiency when the carbon-water suspension was used. The increase is usually in the order of 1% to 2%. Due to the high efficiencies encountered, a relative increase of 1% can result in a relative decrease of 100% in the exit gas stream. The increase in efficiency is therefore quite significant. From low gas flow rates to moderate gas flow rates, neither phi nor the use of the carbon-water suspension seem to have any significant effect.

Effect of Vapor Cycle Time

Figure 13 shows the relationship between the gas mass flow rate and the mass flux with the vapor cycle time, t_{vc}, as a parameter. In the case of low vapor cycle time, the use of carbon has no effect on the mass flux. This indicates that the system is gas phase controlling for low values of t_{vc}. Apparently, at low values of t_{vc} the driving force is so large that the gas cannot supply enough gas at the interface.

At low gas flow rates, the system is also gas phase

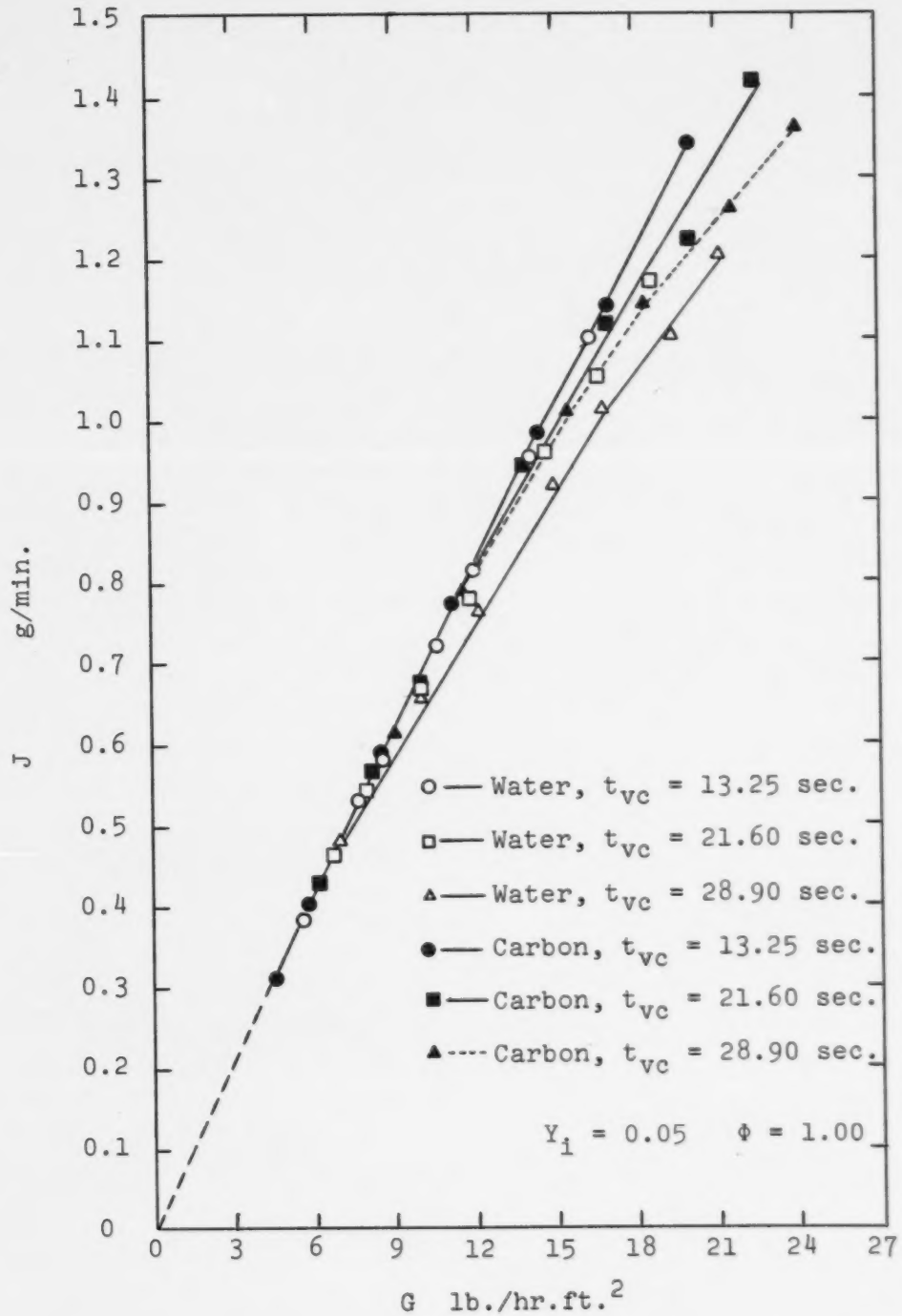

Figure 13.

Cycled Runs with t_{vc} as Parameter
J versus G

controlling, regardless of the vapor cycle time. This is due again to the inability of the gas to deliver SO_2 to the interface fast enough. As the gas flow rate increases, the gas has the SO_2 available to saturate the interface, and the liquid resistance begins to become appreciable. At the higher values of t_{vc} and higher gas flow rates, a distinction can be made between the runs that used carbon and those that used plain water.

Increasing the vapor cycle time decreases the average mass flux over the cycle. This is due to the decrease in the driving force for the added increment of time. At the same time, the concentration of SO_2 is building up in the water. With the carbon present, a sufficient driving force must be formed so that some of the dissolved SO_2 can be adsorbed onto the carbon. This driving force is evidently fairly high as it takes the longest vapor cycle time to show an appreciable effect of the carbon. What might be done at a future date would be to increase the vapor cycle time even more. A profound increase using carbon may be realized at very high values of t_{vc}.

Figure 14 shows the relationship between the gas mass flow rate and the overall efficiency. About the same effect can be noted when t_{vc} is raised as when phi was lowered. The carbon runs show some increase in efficiency, even at the lowest t_{vc}. The increase in efficiency becomes more important as the vapor cycle

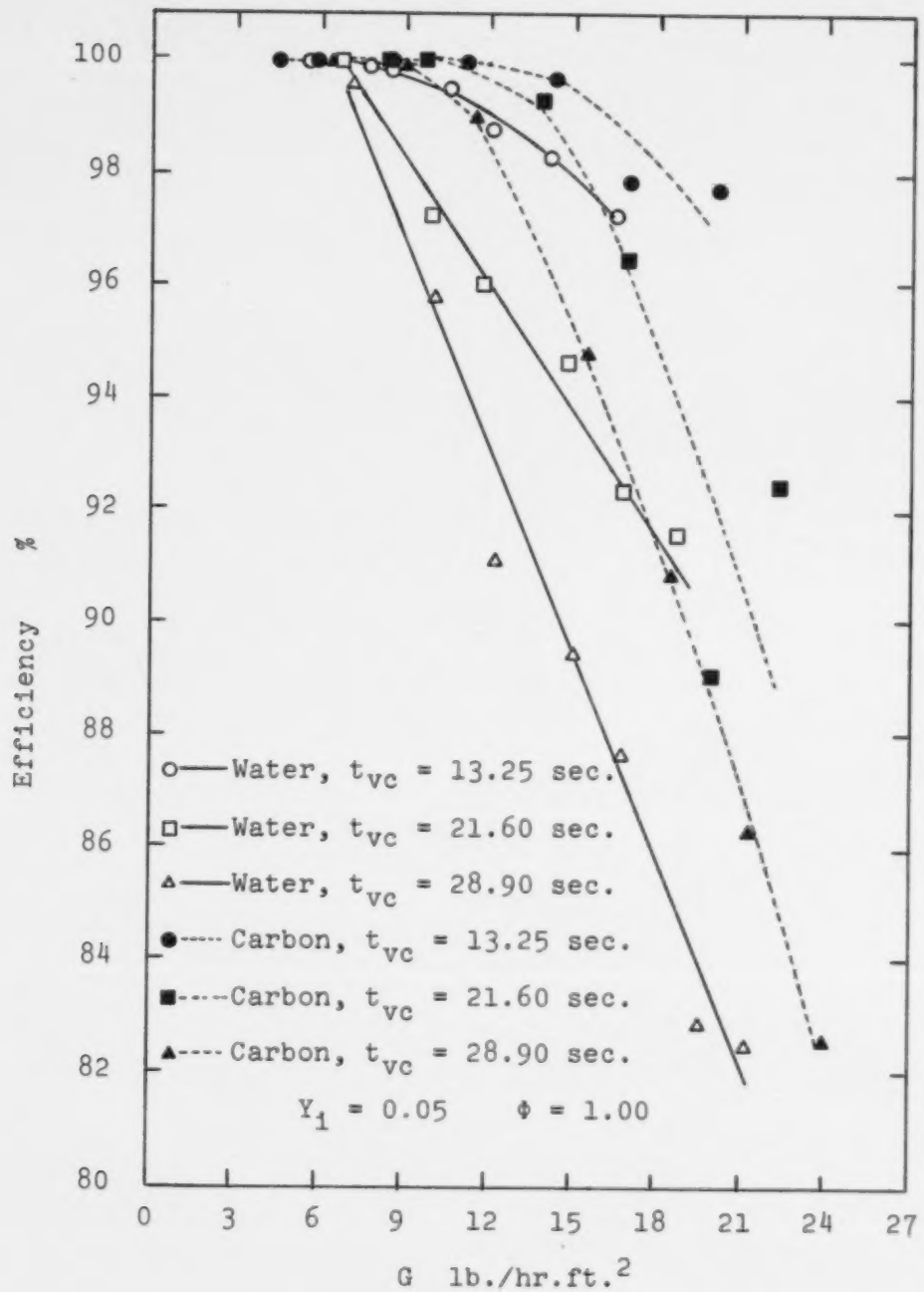

Figure 14.

Cycled Runs with t_{vc} as Parameter
Efficiency versus G

time increases.

Effect of Inlet Concentration of SO_2

Figure 15 shows the relationship between the gas mass flow rate and the mass flux using the inlet concentration of SO_2 as a parameter. For the runs used, phi was 1.0 and the vapor cycle time was low, so that there was no difference between runs with carbon and those with plain water. An explanation of this can be found in the previous two sections.

Assuming that these cycled runs are gas phase controlled, Figure 15 can be explained by Equation 2. Increasing the inlet concentration increases y in Equation 2. It therefore increases the overall driving force. The result is an increase in the mass flux.

Figure 16 shows the relationship between the gas mass flow rate and the overall efficiency. The use of the carbon-water suspension increases the efficiency on the order of 1% to 2%. As was discussed earlier, this is a significant increase considering the high efficiencies attained. The efficiency is independent of the inlet concentration of SO_2. This is due to the interaction of the inlet concentration and the gas mass flow rate.

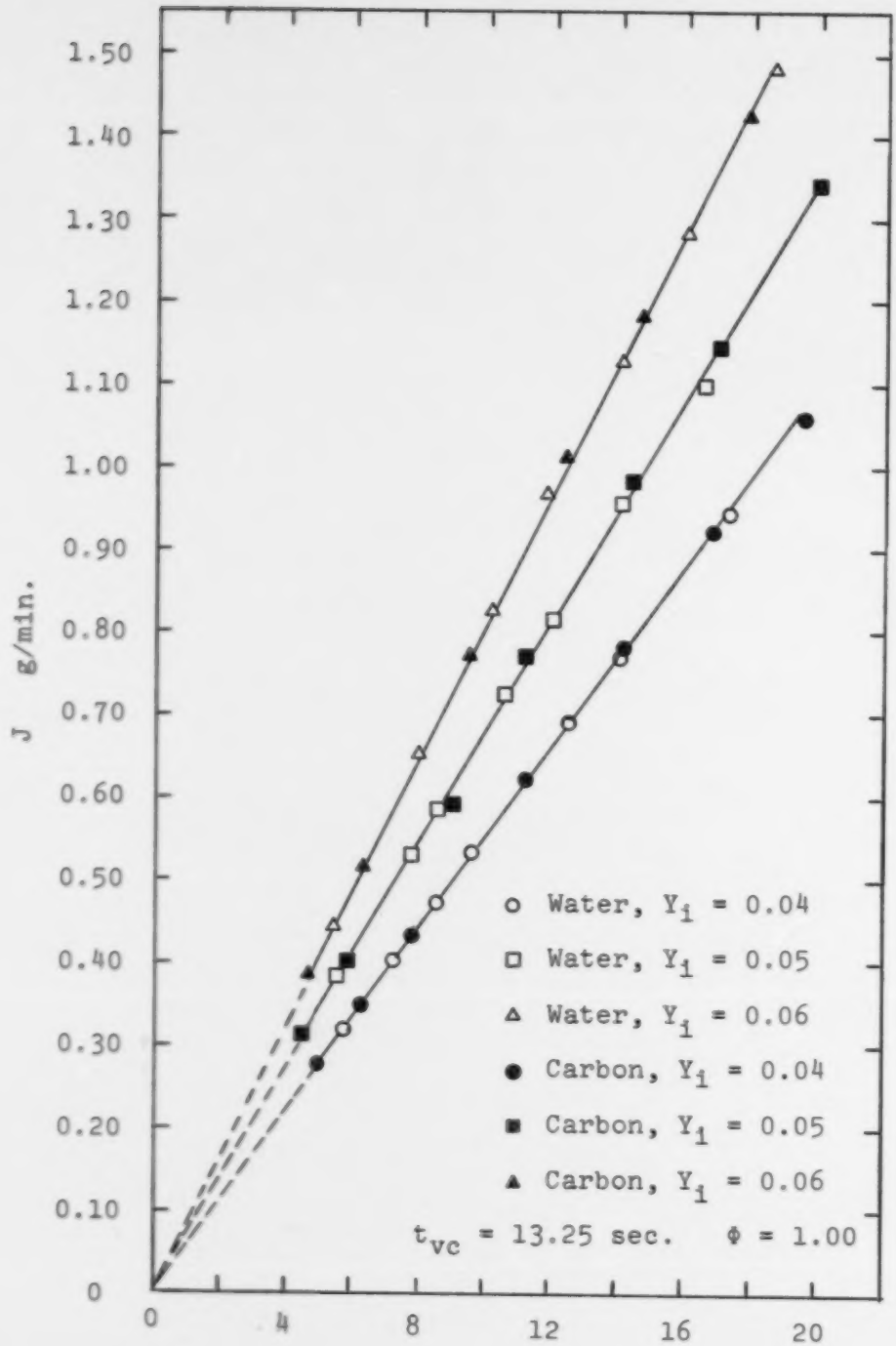

Figure 15.
Cycled Runs with Y_i as Parameter
J versus G

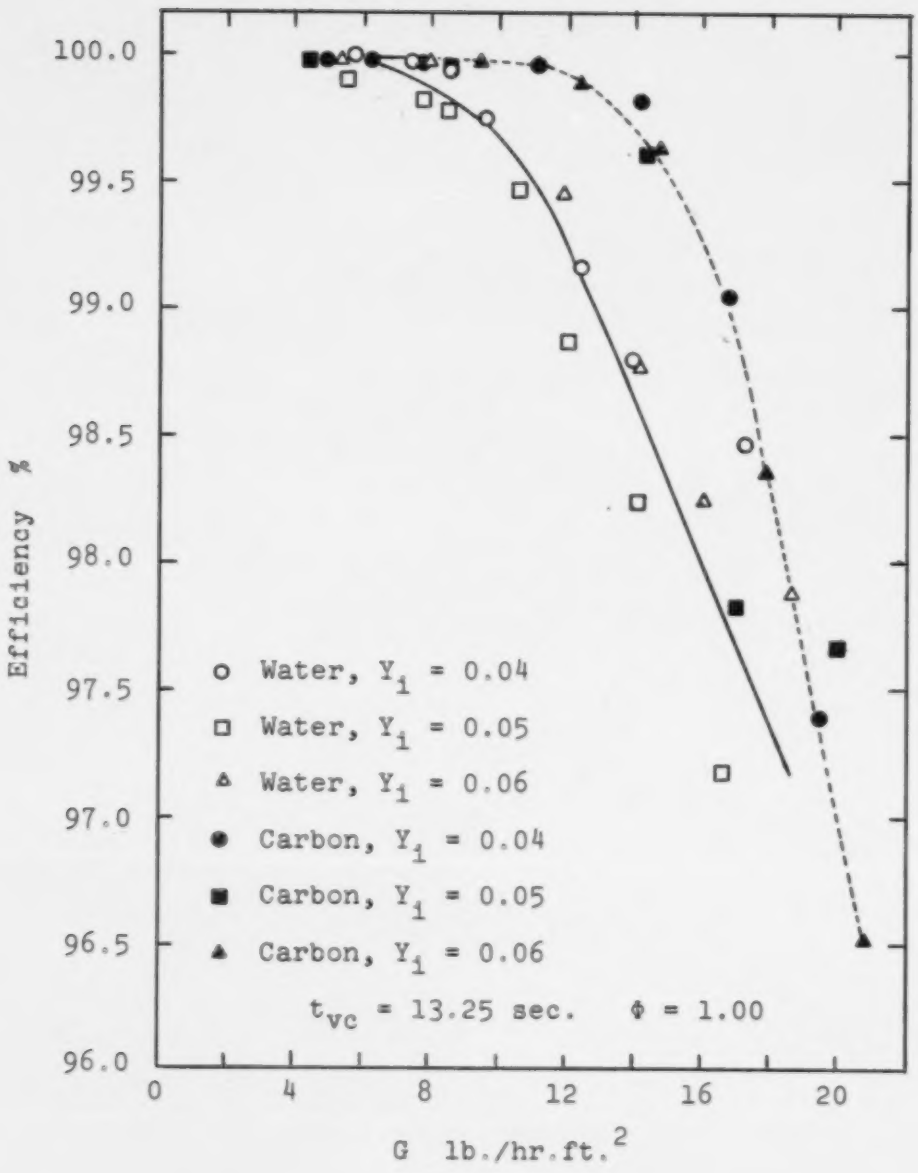

Figure 16.

Cycled Runs with Y_i as Parameter
Efficiency versus G

VI. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions may be drawn from this series of experiments:

1. The use of controlled cycling as a method of column operation for scrubbing SO_2 from air greatly increases the overall efficiency of the column as compared to continuous operations.
2. The use of a carbon-water sorption mixture instead of water increases the efficiency of the column, but not to as great an extent as cycling.
3. Decreasing phi, the fraction of liquid changed on the plate per cycle, decreases the efficiency.
4. Increasing the vapor flow cycle time also decreases the efficiency.
5. The inlet SO_2 concentration and the efficiency are independent of each other.

The equipment for this experiment was comparatively simple to operate, but a few minor changes would facilitate easier operation. During continuous runs, some water must remain in the lower section of the column so that the gas doesn't go up the downcomer or down the drain pipe. Keeping a constant level in this section tended to be difficult. During continuous runs, the liquid was drained from the column through an 1/8-inch pipe and manual valve.

Some type of liquid level control should be integrated into the system. For cycled runs, the liquid level on the plate tended to be erratic. The valve on the liquid inlet side of the column had to be continually adjusted to keep the level somewhat constant.

There are many variations which may be made on this basic experiment. The use of a gas that is more insoluble in water than SO_2 would tend to increase the importance of the carbon. Such a gas might be H_2S. Many parameters in this experiment were held constant which may otherwise be used as variables. Examples of these parameters might be the liquid temperature, the gas temperature, and the amount of carbon in the suspension. The use of a higher gas temperature may more closely approximate flue gas conditions from a power plant.

Further experiments of this type may deal with pulsed flow absorbers, absorbers using a chemical reaction to increase efficiencies, catalytic converters, and packed towers. The results of any of these experiments would help in gaining knowledge on how to rid the air of SO_2.

APPENDIX A

Derivation of the Efficiency Equation

The volumetric flow rate out of the column was first corrected for temperatures and differences in SO_2 concentration to give V_i, the volumetric flow rate into the column. The ideal gas law was assumed for this thesis.

$$V_i = C_1(T_{vo}/T_{vi})\left(\frac{1 - Y_o}{1 - Y_i}\right) V_o$$

The molecular weight of the gas going into the column was then calculated,

$$M.W. = 64.0628(Y_i) + 28.97(1 - Y_i)$$

where 64.0628 and 28.97 are the molecular weights of SO_2 and air respectively. Using the ideal gas law, the mass flow rate of gas into the column was calculated.

$$G = V_i C_2(M.W.)/RT_{vi}C_3A$$

The grams/minute of SO_2 into and out of the column were then calculated, again assuming the ideal gas law.

$$S_i = V_i Y_i C_4/RT_{vi}$$
$$S_o = V_o Y_o C_4/R T_{vo}$$

The overall efficiency can then be calculated.

$$\text{Efficiency} = \frac{S_i - S_o}{S_i} \times 100$$

APPENDIX B

Experimental and Calculated Data

Continuous Runs

Table 1.

Sorption Data - Continuous Run

Liquid used - Carbon and Water

L = 900 cc/minute

Y_i = 0.04

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.27	19.35	74	76	0.0124	0.735	68.27
9.25	17.35	72	79	0.00916	0.739	76.50
8.13	15.22	72	80	0.00547	0.728	85.96
7.03	13.16	72	80	0.00285	0.679	92.69
6.26	11.64	71	84	0.00252	0.605	93.46
5.15	9.56	71	84	0.00121	0.515	96.84
3.97	7.37	71	84	0.000536	0.404	98.61

Table 2.

Sorption Data - Continuous Run

Liquid used - Carbon and Water

L = 540 cc/minute

Y_i = 0.04

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.06	18.81	62	80	0.0140	0.667	63.66
9.67	18.10	62	80	0.0100	0.746	74.03
8.64	16.14	62	81	0.00519	0.779	86.64
7.61	14.21	63	81	0.00351	0.720	90.98
6.46	12.07	63	81	0.00213	0.635	94.53
4.95	9.23	63	82	0.00106	0.499	97.26
4.07	7.58	63	82	0.000571	0.416	98.53

Table 3.

Sorption Data - Continuous Run

Liquid used - Carbon and Water

L = 900 cc/minute

$Y_i = 0.05$

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.56	20.02	60	79	0.0112	1.062	77.10
9.59	18.16	59	80	0.00817	1.041	83.35
8.75	16.50	59	82	0.00379	1.047	92.24
7.48	14.06	59	84	0.00145	0.938	97.01
6.59	12.40	59	83	0.00154	0.826	96.83
5.05	9.46	59	85	0.000717	0.641	98.52
4.11	7.71	59	85	0.000366	0.526	99.24

Table 4.

Sorption Data - Continuous Run

Liquid used - Carbon and Water

L = 540 cc/minute

Y_i = 0.05

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.50	20.10	65	74	0.0143	0.985	71.21
9.74	18.61	65	75	0.0105	1.009	78.83
8.83	16.81	66	77	0.00544	1.030	89.03
7.81	14.81	65	79	0.00424	0.931	91.39
6.41	12.12	66	80	0.00246	0.792	94.99
5.01	9.48	66	80	0.00132	0.635	97.30
4.02	7.60	66	81	0.000863	0.513	98.24

Table 5.

Sorption Data - Continuous Run

Liquid used - Carbon and Water

L = 900 cc/minute

Y_i = 0.06

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.13	19.60	65	74	0.0127	1.262	78.87
9.43	18.22	66	75	0.00730	1.308	87.94
8.06	15.51	66	77	0.00490	1.163	91.86
7.34	14.07	65	79	0.00244	1.102	95.92
6.58	12.60	66	80	0.00344	0.969	94.24
5.37	10.27	66	80	0.00132	0.820	97.78
3.55	6.80	66	80	0.000281	0.553	99.53

Table 6.

Sorption Data - Continuous Run

Liquid used - Carbon and Water

L = 540 cc/minute

Y_i = 0.06

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.35	19.80	65	80	0.0163	1.170	72.40
9.20	17.62	65	80	0.0101	1.192	82.88
8.13	15.53	65	81	0.00706	1.117	88.11
7.31	13.97	66	81	0.00538	1.037	90.95
5.89	11.25	66	81	0.00242	0.881	95.94
4.95	9.45	66	82	0.00117	0.756	98.03
3.99	7.62	66	82	0.000942	0.612	98.41

Table 7.

Absorption Data - Continuous Runs

Liquid used - water

L = 900 cc/minute

Y_1 = 0.04

V_i	G	T_1	T_{vi}	Y_o	J	Efficiency
13.92	26.05	60	80	0.00852	1.132	78.09
12.48	23.39	60	79	0.00674	1.077	82.74
10.28	19.30	60	78	0.00582	0.915	85.18
9.20	17.28	60	78	0.00509	0.837	87.03
7.14	13.39	60	79	0.00433	0.663	88.94
5.41	10.15	60	79	0.00306	0.521	92.19
3.92	7.35	60	79	0.00182	0.390	95.36

Table 8.

Absorption Data - Continuous Runs

Liquid used - Water

L = 540 cc/minute

Y_i = 0.04

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.79	25.85	60	79	0.0166	0.821	57.04
12.18	22.84	62	79	0.0151	0.773	60.85
9.98	18.70	62	79	0.0110	0.745	71.57
9.01	16.86	63	80	0.0112	0.666	70.94
6.94	12.96	63	81	0.00746	0.582	80.75
4.89	9.12	61	82	0.00495	0.443	87.21
3.71	6.92	60	82	0.00345	0.351	91.10

Table 9.

Absorption Data - Continuous Runs

Liquid used - Water

L = 900 cc/minute

Y_i = 0.05

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
14.22	26.76	61	83	0.0218	1.016	55.20
12.32	23.10	58	85	0.0120	1.197	75.33
10.26	19.24	58	85	0.00965	1.063	80.32
8.43	15.81	58	85	0.00750	0.922	84.73
6.21	11.65	58	85	0.00498	0.720	89.88
3.76	7.06	58	85	0.00107	0.475	97.82

Table 10.

Absorption Data - Continuous Runs

Liquid used - Water

L = 540 cc/minute

$Y_1 = 0.05$

V_1	G	T_1	T_{vi}	Y_o	J	Efficiency
14.62	27.82	60	77	0.0253	0.930	48.60
12.21	23.15	60	79	0.0199	0.952	59.81
10.62	20.03	60	82	0.0161	0.926	67.16
9.30	17.51	60	83	0.0140	0.862	71.52
7.48	14.07	60	83	0.0123	0.726	75.01
5.07	9.53	60	84	0.00895	0.536	81.82
4.02	7.55	60	84	0.00283	0.489	94.28

Table 11.

Absorption Data - Continuous Runs

Liquid used - Water

L = 900 cc/minute

Y_i = 0.06

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.90	26.85	59	75	0.0147	1.654	75.46
12.61	24.27	59	77	0.0128	1.558	78.64
10.70	20.55	59	78	0.0105	1.381	82.31
9.33	17.90	59	79	0.00982	1.221	83.54
7.33	14.01	58	81	0.0144	0.866	75.70
4.94	9.40	57	83	0.00619	0.687	89.59
3.66	6.965	57	83	0.00381	0.532	93.61

Table 12.

Absorption Data - Continuous Runs

Liquid used - Water

L = 540 cc/minute

Y_i = 0.06

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.26	25.28	58	82	0.0280	1.074	52.06
12.06	23.03	58	81	0.0173	1.330	70.75
10.65	20.38	58	80	0.0197	1.109	66.63
9.18	17.58	58	80	0.0149	1.075	74.93
7.21	13.81	58	80	0.0177	0.791	70.20
5.00	9.57	58	80	0.00778	0.680	87.04
3.98	7.62	59	80	0.00623	o.558	89.64

APPENDIX C

Experimental and Calculated Data

Cycled Runs

Table 13.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 902.51 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.04 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.42	19.56	59	78	0.00102	1.061	97.39
8.94	16.76	59	79	0.000370	0.924	99.05
7.56	14.18	59	79	0.000072	0.788	99.81
6.00	11.22	59	80	0.000018	0.624	99.95
4.16	7.80	59	79	0.000012	0.434	99.96
3.36	6.29	60	80	0.000006	0.350	99.98
2.65	4.98	59	77	0.000006	0.277	99.98

Table 14.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water

t_{lc} = 7.15 seconds

L = 639.28 cc/minute

t_{vc} = 21.65 seconds

Y_i = 0.04

Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.80	22.25	56	76	0.00334	1.134	91.55
10.42	19.57	55	78	0.00212	1.031	94.60
9.04	16.97	55	78	0.00139	0.911	96.47
7.25	13.57	56	80	0.000248	0.751	99.36
5.63	10.51	56	81	0.000051	0.584	99.86
4.62	8.59	57	83	0.000014	0.478	99.96
3.00	5.60	55	81	0.000008	0.311	99.97

Table 15.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 510.71 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.04 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.25	22.66	56	86	0.00848	0.983	77.95
11.11	20.56	57	86	0.00497	0.997	87.11
9.58	17.73	57	86	0.00399	0.885	89.65
7.88	14.55	59	87	0.00174	0.773	95.48
6.14	11.35	59	87	0.000324	0.626	99.15
4.50	8.32	59	87	0.000051	0.462	99.86
3.36	6.20	59	88	0.000014	0.345	99.96

Table 16.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 765.87 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.04 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.53	23.45	59	80	0.00293	1.207	92.49
11.38	21.28	59	80	0.00316	1.089	91.90
9.71	18.17	59	80	0.00151	0.972	96.14
7.74	14.47	59	80	0.000316	0.799	99.19
6.12	11.45	59	80	0.000083	0.636	99.78
4.69	8.78	59	80	0.000017	0.489	99.95
2.71	5.07	59	80	0.000008	0.282	99.97

Table 17.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 522.65 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.04 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Effeciency
12.69	23.52	65	85	0.00697	1.073	81.96
11.19	20.75	65	85	0.00475	1.013	87.74
9.72	18.02	65	85	0.00414	0.896	89.30
7.86	14.57	65	85	0.00138	0.782	96.43
5.94	11.00	58	86	0.000408	0.606	98.94
4.85	8.97	58	86	0.000078	0.498	99.79
2.92	5.40	58	86	0.000012	0.300	99.96

Table 18.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water

L = 410.21 cc/minute

Y_i = 0.04

t_{lc} = 4.80 seconds

t_{vc} = 28.90 seconds

Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.21	24.94	63	75	0.00882	1.079	77.72
11.66	22.01	63	75	0.00757	0.990	80.82
9.92	18.53	65	81	0.00507	0.897	86.94
8.17	15.24	65	82	0.00186	0.807	95.20
6.02	11.20	65	83	0.000752	0.611	98.06
4.62	8.59	65	84	0.000042	0.477	99.88
2.89	5.37	65	85	0.000016	0.298	99.95

Table 19.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 572.31 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.04 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.72	25.91	60	75	0.00632	1.212	84.01
12.52	23.65	60	75	0.00502	1.149	87.31
10.59	19.96	61	76	0.00292	1.029	92.63
8.69	16.37	61	76	0.00140	0.879	96.47
6.83	12.85	61	77	0.000409	0.708	98.96
4.79	9.00	61	78	0.000068	0.500	99.82
3.01	5.63	61	80	0.000012	0.313	99.96

Table 20.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water

t_{lc} = 3.00 seconds

L = 377.28 cc/minute

t_{vc} = 21.65 seconds

Y_i = 0.04

Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.90	25.95	63	81	0.00892	1.112	76.94
12.26	22.90	64	81	0.00932	0.968	75.90
10.57	19.75	64	81	0.00591	0.932	84.77
8.54	15.93	64	82	0.00246	0.830	93.65
6.70	12.49	64	82	0.00135	0.671	96.50
4.70	8.77	64	82	58.9848	0.000	99.40
2.89	5.399	64	82	0.00026	0.300	99.93

Table 21.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 291.54 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.04 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
14.52	27.47	68	74	0.0145	0.964	63.05
13.08	24.65	69	76	0.0144	0.865	63.01
11.46	21.51	69	78	0.0113	0.849	70.93
9.87	18.51	69	79	0.00641	0.861	83.59
7.34	13.74	69	80	0.00387	0 689	90.07
4.88	9.13	69	80	0.000760	0.498	98.05
3.19	5.96	68	81	0.000053	0.331	99.86

Table 22.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 902.51 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.05 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.58	20.01	59	80	0.00114	1.345	97.67
8.99	16.99	59	81	0.00105	1.144	97.86
7.61	14.38	59	81	0.000192	0.986	99.60
5.95	11.22	60	82	0.000026	0.771	99.94
4.59	8.63	58	83	0.000015	0.594	99.96
3.11	5.86	58	83	0.000006	0.403	99.98
2.40	4.52	58	84	0.000002	0.311	99.99

Table 23.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 639.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.05 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.87	22.35	56	83	0.00367	1.421	92.46
10.61	19.97	57	83	0.00532	1.224	89.07
8.98	16.91	57	83	0.00175	1.121	96.40
7.35	13.83	56	83	0.000383	0.944	99.21
5.30	9.96	56	84	0.000044	0.684	99.90
4.43	8.32	56	84	0.000014	0.572	99.96
3.32	6.25	56	84	0.000003	0.430	99.99

Table 24.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 510.71 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.05 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.61	24.05	65	76	0.00865	1.366	82.56
11.21	21.34	65	77	0.00680	1.266	86.27
9.71	18.41	66	79	0.00458	1.149	90.71
8.21	15.54	66	80	0.00259	1.013	94.74
6.14	11.54	66	84	0.000515	0.785	98.94
4.78	8.98	66	84	0.000075	0.617	99.84
3.38	6.34	66	85	0.000012	0.436	99.97

Table 25.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water

t_{lc} = 4.80 seconds

L = 765.87 cc/minute

t_{vc} = 13.25 seconds

Y_i = 0.05

Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.74	24.34	60	75	0.00410	1.538	91.81
11.06	21.09	59	76	0.00290	1.366	94.19
9.39	17.91	59	76	0.00186	1.186	96.27
8.01	15.25	59	77	0.000620	1.036	98.75
6.36	12.08	59	78	0.000144	0.829	99.70
4.69	8.90	59	78	0.000028	0.612	99.94
3.14	5.98	60	78	0.000008	0.411	99.98

Table 26.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 522.65 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.05 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.43	23.43	60	86	0.00759	1.347	84.20
11.02	20.63	60	86	0.00692	1.215	85.60
9.45	17.66	61	87	0.00442	1.104	90.86
7.67	14.33	61	87	0.00162	0.953	96.66
5.69	10.64	61	87	0.000352	0.726	99.27
4.81	8.99	61	87	0.000079	0.617	99.83
2.62	4.89	61	87	0.000016	0.336	99.96

Table 27.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 410.21 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.05 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.22	24.22	64	84	0.0110	1.316	77.07
11.74	22.02	64	85	0.0117	1.144	75.51
9.87	18.50	64	85	0.00680	1.093	85.91
8.12	15.23	64	85	0.00458	0.948	90.52
6.02	11.30	64	85	0.000811	0.764	98.32
4.43	8.31	64	85	0.000128	0.570	99.73
3.15	5.92	64	85	0.000032	0.040	99.93

Table 28.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 572.31 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.05 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.60	25.67	62	81	0.00851	1.460	82.61
12.32	23.23	60	82	0.00595	1.403	87.82
10.68	20.13	61	82	0.00479	1.249	90.20
8.87	16.69	61	83	0.00307	1.076	93.69
6.81	12.80	61	84	0.000581	0.870	98.80
5.12	9.62	61	84	0.000156	0.660	99.67
2.94	5.54	61	84	0.000020	0.381	99.95

Table 29.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 377.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.05 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
14.46	27.62	61	75	0.0146	1.340	70.53
12.29	23.44	64	76	0.0110	1.252	77.68
10.30	19.65	64	76	0.00784	1.138	84.22
8.88	16.86	63	78	0.00527	1.036	89.32
7.39	14.02	64	79	0.00266	0.912	94.60
5.01	9.49	64	80	0.000568	0.645	98.85
2.68	5.077	64	81	0.000028	0.349	99.94

Table 30.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 291.54 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.05 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
14.32	26.99	66	82	0.0;968	1.099	59.17
12.76	24.05	66	82	0.0188	1.009	60.98
10.86	20.47	66	82	0.0134	1.018	72.28
8.80	16.59	65	82	0.00625	0.995	87.19
6.46	12.18	65	82	0.00292	0.788	94.03
4.67	8.80	65	82	0.000796	0.596	98.37
2.92	5.50	65	82	0.000075	0.378	99.84

Table 31.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 902.51 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.06 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.71	20.76	61	73	0.00213	1.636	96.51
9.19	17.79	61	74	0.00101	1.428	98.34
7.52	14.54	61	75	0.000222	1.182	99.63
6.45	12.41	61	77	0.000064	1.012	99.89
4.91	9.43	61	78	0.000007	0.770	99.98
3.31	6.36	56	79	0.000007	0.519	99.98
2.48	4.75	56	79	0.000003	0.388	99.99

Table 32.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 639.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.06 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.00	22.98	57	80	0.00529	1.709	91.13
10.66	20.40	57	80	0.00316	1.577	94.72
8.88	16.99	57	80	0.00155	1.351	97.41
7.45	14.25	57	80	0.000666	1.151	98.88
5.65	10.82	55	80	0.000133	0.881	99.77
4.31	8.12	55	81	0.000021	0.672	99.96
3.39	6.47	56	82	0.000009	0.528	99.98

Table 33.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 7.15 seconds

L = 510.71 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.06 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.54	23.70	64	87	0.0118	1.544	79.82
11.36	21.47	64	87	0.00787	1.517	86.59
9.37	17.70	64	87	0.00383	1.351	93.49
7.89	14.89	64	88	0.00201	1.174	96.58
6.19	11.67	64	88	0.00220	0.917	96.25
5.33	10.05	64	88	0.000274	0.816	99.53
3.14	5.92	64	89	0.000020	0.483	99.96

Table 34.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 765.87 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.06 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.24	21.40	57	83	0.00678	1.546	88.50
9.72	18.50	57	83	0.00260	1.443	95.59
7.87	14.95	56	84	0.00121	1.196	97.95
6.70	12.73	56	84	0.000676	1.027	98.85
5.50	10.45	56	84	0.000094	0.851	99.84
3.83	7.29	56	83	0.000020	0.595	99.96
2.59	4.94	57	82	0.000009	0.403	99.98

Table 35.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 522.65 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.06 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
12.73	24.51	56	77	0.0102	1.658	82.87
11.68	22.44	56	78	0.00641	1.636	89.33
9.90	19.02	56	78	0.00511	1.421	91.51
8.09	15.49	56	80	0.00251	1.211	95.80
6.45	12.34	56	80	0.00106	0.989	98.22
4.94	9.45	57	81	0.000143	0.769	99.75
2.78	5.32	57	81	0.000015	0.434	99.97

Table 36.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 4.80 seconds

L = 410.21 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.06 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.61	26.05	60	80	0.0141	1.619	76.15
12.45	23.79	62	81	0.0121	1.544	79.51
10.94	20.87	62	82	0.00952	1.429	83.88
9.04	17.24	62	82	0.00494	1.290	91.66
7.05	13.45	62	82	0.00196	1.061	96.69
5.52	10.51	62	83	0.000656	0.848	98.89
3.37	6.41	62	84	0.000056	0.523	99.90

Table 37.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 572.31 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.06 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
13.51	26.16	60	74	0.00893	1.821	85.27
12.20	23.57	59	75	0.00684	1.707	88.69
10.52	20.28	58	76	0.00448	1.533	92.58
9.30	17.86	59	78	0.00276	1.391	95.40
6.57	12.63	59	78	0.000800	1.017	98.67
5.14	9.85	58	79	0.000177	0.802	99.70
3.07	5.90	59	79	0.000020	0.481	99.96

Table 38.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 377.28 cc/minute t_{vc} = 21.65 seconds

Y_1 = 0.06 Φ = 0.50

V_1	G	T_1	T_{v1}	Y_o	J	Efficiency
14.33	27.43	63	80	0.0180	1.552	69.33
12.47	23.83	62	81	0.0133	1.505	77.35
10.77	20.57	62	81	0.00895	1.426	84.90
8.93	17.07	62	81	0.00604	1.251	89.83
7.17	13.68	62	82	0.00271	1.066	95.43
5.27	10.05	62	82	0.000082	0.809	98.61
2.73	5.21	61	82	0.000041	0.425	99.92

Table 39.

Sorption Data - Cycled Runs

Liquid used - Carbon and Water t_{lc} = 3.00 seconds

L = 291.54 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.06 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
14.68	28.00	67	82	0.0241	1.336	58.48
13.15	25.08	67	82	0.0206	1.324	64.70
10.91	20.80	67	82	0.0159	1.237	72.85
9.57	18.25	67	82	0.0105	1.225	82.20
7.85	14.98	67	82	0.00630	1.092	89.35
5.26	10.04	67	82	0.00192	0.793	96.76
2.36	4.50	67	82	0.000079	0.367	99.86

Table 40.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 902.51 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.04 ϕ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
9.13	17.25	56	75	0.000552	0.947	98.61
7.41	13.97	56	76	0.000474	0.768	98.80
6.63	12.48	57	77	0.000264	0.690	99.33
5.13	9.63	58	78	0.000092	0.535	99.76
4.57	8.59	58	78	0.000026	0.478	99.93
3.87	7.26	58	78	0.000010	0.404	99.97
3.07	5.75	59	80	0.000002	0.320	99.99

Table 41.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 639.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.04 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.62	19.90	60	79	0.00361	1.006	90.79
9.16	17.17	60	79	0.00191	0.090	95.13
7.92	14.84	61	79	0.00172	0.790	95.62
6.56	12.28	61	80	0.000834	0.669	97.87
5.38	10.04	61	81	0.000330	0.554	99.15
4.24	7.92	61	81	0.000029	0.440	99.92
3.56	6.64	61	81	0.000008	0.370	99.97

Table 42.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 510.71 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.04 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.80	20.47	65	73	0.00588	0.971	85.18
10.12	19.10	67	75	0.00595	0.093	84.95
9.09	17.11	67	77	0.00534	0.823	86.40
7.65	14.36	66	78	0.00613	0.675	84.38
6.41	11.99	66	80	0.00275	0.620	92.95
5.63	10.56	66	79	0.000911	0.574	97.68
3.59	6.72	66	80	0.000138	0.373	99.64

Table 43.

Absorption Data - Cycled Runs

Liquid used - Water

t_{lc} = 4.80 seconds

L = 765.87 cc/minute

t_{vc} = 13.25 seconds

Y_i = 0.04

Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
9.99	18.86	61	75	0.00104	1.022	97.36
9.02	17.03	60	75	0.00109	0.922	97.23
7.92	14.96	60	75	0.000771	0.817	98.06
6.74	12.71	59	76	0.000781	0.694	98.02
5.92	11.15	58	76	0.000497	0.613	98.74
4.59	8.65	58	76	0.000121	0.480	99.69
3.06	5.76	58	76	0.000008	0.321	99.97

Table 44.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 522.65 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.04 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
9.67	17.98	54	83	0.00234	0.941	93.99
8.77	16.31	54	83	0.00205	0.860	94.72
7.70	14.30	54	84	0.00465	0.700	87.99
6.91	12.84	54	84	0.00150	0.687	96.13
6.02	11.18	54	84	0.00107	0.605	97.23
4.76	8.85	54	84	0.000450	0.487	98.84
3.78	7.01	54	84	0.000055	0.390	99.85

Table 45.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 410.21 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.04 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.43	19.51	53	80	0.00578	0.925	85.17
9.30	17.37	51	81	0.00769	0.775	80.15
8.69	16.20	51	82	0.00883	0.697	77.27
7.06	13.16	51	82	0.00864	0.570	77.76
6.17	11.49	51	83	0.00227	0.602	94.16
5.57	10.39	51	82	0.00137	0.558	96.48
4.20	7.85	51	81	0.000260	0.434	99.33

Table 46.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 572.31 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.04 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.58	19.95	58	76	0.00529	0.961	86.58
9.21	17.37	58	76	0.00229	0.911	94.18
8.24	15.56	60	75	0.00194	0.824	95.11
7.20	13.60	60	75	0.00202	0.718	94.90
6.47	12.22	60	75	0.00120	0.659	96.95
4.99	9.43	61	75	0.000371	0.520	99.06
3.55	6.71	61	75	0.000038	0.373	99.90

Table 47.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 377.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.04 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.38	21.49	57	75	0.00764	0.965	80.65
9.79	18.46	58	76	0.00717	0.840	81.78
8.88	16.70	59	77	0.00475	0.817	87.90
7.70	14.49	61	77	0.00383	0.728	90.25
5.80	10.89	61	78	0.00380	0.547	90.28
5.02	9.45	62	77	0.00163	0.504	95.84
3.93	7.40	62	77	0.00046	0.407	98.86

Table 48.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 291.54 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.04 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.99	20.76	62	75	0.0117	0.811	70.22
9.87	18.60	64	76	0.0105	0.757	73.13
8.83	16.55	61	79	0.0247	0.326	35.42
7.78	14.55	56	80	0.00580	0.689	85.12
6.81	12.71	55	81	0.00426	0.630	89.05
5.91	11.04	54	81	0.00494	0.536	87.27
4.97	9.26	53	82	0.00175	0.492	95.48

Table 49.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 902.51 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.05 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
8.66	16.45	55	78	0.00141	1.100	97.19
7.45	14.11	55	80	0.000885	0.954	98.24
6.38	12.00	56	83	0.000559	0.816	98.87
5.64	10.61	57	83	0.000263	0.726	99.47
4.52	8.52	58	82	0.000107	0.585	99.78
4.10	7.74	56	82	0.000085	0.531	99.82
2.97	5.60	56	82	0.000046	0.385	99.07

Table 50.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 639.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.05 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
9.76	18.65	56	75	0.00428	1.175	91.54
8.76	16.70	56	76	0.00393	1.059	92.19
7.76	14.77	56	77	0.00270	0.961	94.63
6.22	11.85	57	77	0.00201	0.782	96.00
5.28	10.03	58	78	0.00140	0.670	97.20
4.18	7.95	59	78	0.000099	0.546	99.80
3.56	6.77	60	78	0.000017	0.465	99.96

Table 51.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 510.71 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.05 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.09	21.19	60	75	0.00883	1.202	82.48
10.23	19.41	62	79	0.00861	1.106	82.85
8.85	16.80	61	78	0.00623	1.013	87.67
7.90	14.95	63	80	0.00528	0.920	89.47
6.36	12.21	63	81	0.00446	0.765	91.09
5.31	10.05	63	80	0.00212	0.662	95.77
3.71	7.03	63	80	0.0000243	0.481	99.51

Table 52.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 765.87 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.05 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
9.98	19.03	57	76	0.00227	1.249	95.45
8.83	16.84	57	76	0.00280	1.093	94.39
7.39	14.10	58	76	0.00179	0.935	96.41
5.58	10.65	58	76	0.000603	0.724	98.79
4.88	9.31	59	76	0.000207	0.637	99.58
4.21	8.02	59	76	0.000046	0.551	99.90
2.76	5.26	60	76	0.000008	0.362	99.98

Table 53.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 522.65 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.05 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.03	19.05	55	78	0.00444	1.193	91.04
8.96	16.99	55	79	0.00493	1.052	90.01
7.77	14.71	54	80	0.00453	0.919	90.86
6.82	12.86	54	82	0.00343	0.823	93.04
6.10	11.46	54	84	0.00239	0.749	95.11
4.83	9.09	54	84	0.000682	0.616	98.61
3.59	6.74	54	84	0.000221	0.462	99.55

Table 54.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 410.21 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.05 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.47	20.05	52	74	0.0108	1.081	78.35
9.63	18.43	52	74	0.00591	1.118	88.20
8.94	17.08	52	75	0.00651	1.022	87.01
7.85	14.94	51	77	0.00820	0.859	83.61
6.40	12.11	51	80	0.00279	0.786	94.38
5.67	10.74	51	80	0.00370	0.684	92.54
4.43	8.39	51	80	0.000702	0.569	98.59

Table 55.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 572.31 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.05 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.80	20.68	60	74	0.00589	1.255	88.20
9.48	18.11	60	75	0.00401	1.146	92.02
8.09	15.43	60	76	0.00305	0.997	93.90
7.15	13.61	61	77	0.00256	0.888	94.87
6.03	11.49	61	77	0.00202	0.758	95.95
4.29	8.17	62	77	0.000314	0.558	99.37
3.13	5.96	62	77	0.000033	0.410	99.93

Table 56.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 377.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.05 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.18	21.24	62	78	0.0103	1.155	79.05
9.73	18.49	62	78	0.0188	0.784	61.64
8.65	16.43	62	78	0.0158	0.767	67.93
7.78	14.78	62	78	0.0121	0.767	75.43
6.43	12.22	63	78	0.0100	0.670	79.71
5.38	10.22	63	78	0.00632	0.614	87.30
4.30	8.17	64	78	0.00143	0.546	97.12

Table 57.

Absorption Data - Cycled Runs

Liquid used - Water

t_{lc} = 3.00 seconds

L = 291.54 cc/minute

t_{vc} = 28.90 seconds

Y_i = 0.05

Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.24	21.34	58	78	0.0104	1.159	78.91
10.08	19.11	58	79	0.0130	0.967	73.59
9.15	17.35	58	79	0.0098	0.955	80.00
8.06	15.26	58	80	0.0123	0.787	74.96
6.70	12.68	58	80	0.00816	0.729	83.50
5.98	11.31	58	80	0.00952	0.628	80.73
4.55	8.60	59	80	0.00183	0.570	96.32

Table 58.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 902.51 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.06 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
9.68	18.60	62	78	0.00129	1.486	97.87
8.33	16.01	62	78	0.00106	1.284	98.25
7.30	14.00	63	79	0.000712	1.129	98.82
6.21	11.88	62	80	0.000331	0.964	99.45
5.30	10.12	61	81	0.000128	0.825	99.78
4.18	7.98	61	82	0.000016	0.651	99.97
2.84	5.41	61	82	0.000005	0.442	99.99

Table 59.

Absorption Data - Cycled Runs

Liquid used - Water

t_{lc} = 7.15 seconds

L = 639.28 cc/minute

t_{vc} = 21.65 seconds

Y_i = 0.06

Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.58	20.25	60	80	0.00432	1.534	92.81
9.61	18.39	60	80	0.00645	1.340	89.26
8.03	15.37	60	80	0.00294	1.193	95.12
6.31	12.09	61	80	0.00287	0.939	95.23
5.26	10.08	61	80	0.000878	0.811	98.54
4.34	8.30	61	81	0.000278	0.675	99.53
3.18	6.08	62	81	0.000012	0.496	99.97

Table 60.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 7.15 seconds

L = 510.71 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.06 Φ = 1.00

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.94	20.94	65	80	0.00882	1.458	85.29
9.57	18.31	64	80	0.00777	1.301	87.06
8.77	16.79	64	80	0.00618	1.230	89.71
7.89	15.10	64	80	0.00493	1.132	91.81
6.72	12.87	64	80	0.00451	0.972	92.50
4.97	9.51	64	80	0.000573	0.769	99.05
3.81	7.30	63	79	0.000194	0.594	99.68

Table 61.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 765.87 cc/minute t_{vc} = 13.25 seconds

Y_i = 0.06 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.20	19.75	55	74	0.00445	1.495	92.72
9.35	18.10	55	74	0.00475	1.362	92.21
8.41	16.25	55	75	0.00142	1.295	97.66
7.40	14.27	56	76	0.00229	1.121	96.23
5.64	10.88	56	76	0.00100	0.873	98.34
4.24	8.17	57	77	0.000105	0.666	99.82
3.22	6.19	57	78	0.000011	0.505	99.98

Table 62.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 522.65 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.06 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.03	19.48	51	72	0.00647	1.422	89.38
8.74	16.96	51	73	0.0109	1.133	81.86
8.00	15.70	51	67	0.00764	1.121	87.46
7.27	14.24	51	68	0.00408	1.085	93.29
5.76	11.28	51	68	0.00160	0.896	97.38
4.75	9.29	51	69	0.00123	0.743	97.97
3.83	7.48	51	69	0.000408	0.606	99.32

Table 63.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 4.80 seconds

L = 410.21 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.06 Φ = 0.75

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.25	19.58	51	81	0.00438	1.481	92.65
9.64	18.41	51	81	0.00817	1.296	86.23
9.23	17.64	51	81	0.0112	1.168	81.14
8.23	15.72	51	81	0.0173	0.907	70.65
6.84	13.09	51	80	0.00876	0.912	85.38
5.52	10.57	51	80	0.00297	0.820	95.07
4.59	8.78	51	80	0.00127	0.702	97.88

Table 64.

Absorption Data - Cycled Runs

Liquid used - Water

t_{lc} = 3.00 seconds

L = 572.31 cc/minute

t_{vc} = 13.25 seconds

Y_i = 0.06

Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
10.51	20.27	56	76	0.00683	1.468	88.70
9.52	18.36	55	76	0.00416	1.394	92.97
8.46	16.32	56	76	0.00499	1.222	91.77
7.44	14.35	57	76	0.00550	1.065	90.93
6.38	12.27	57	77	0.00576	0.906	90.45
4.63	8.92	57	77	0.00111	0.715	98.16
3.51	6.75	58	77	0.000161	0.549	99.73

Table 65.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 377.28 cc/minute t_{vc} = 21.65 seconds

Y_i = 0.06 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.61	22.44	57	75	0.0102	1.521	83.05
10.14	19.56	58	76	0.00750	1.390	97.60
9.11	17.56	59	76	0.0124	1.138	79.40
8.03	15.48	59	76	0.00869	1.084	85.77
6.19	11.95	60	76	0.00548	0.887	90.95
5.12	9.88	61	76	0.00222	0.776	96.33
4.30	8.27	60	77	0.00100	0.664	98.34

Table 66.

Absorption Data - Cycled Runs

Liquid used - Water t_{lc} = 3.00 seconds

L = 291.54 cc/minute t_{vc} = 28.90 seconds

Y_i = 0.06 Φ = 0.50

V_i	G	T_l	T_{vi}	Y_o	J	Efficiency
11.28	21.80	61	75	0.0253	1.023	57.52
10.02	19.35	61	75	0.0166	1.141	72.27
9.11	17.57	62	76	0.0206	0.939	65.49
7.62	14.70	63	76	0.0103	0.993	82.77
6.61	12.69	65	78	0.00750	0.906	87.50
5.83	11.18	59	79	0.00518	0.833	91.35
4.61	8.83	58	80	0.00197	0.697	96.70

APPENDIX D

Description of Activated Carbon

The activated carbon used was produced by Westvaco, formerly known as West Virginia Pulp and Paper Company. It is called by the brandname of Nuchar 190-C and is powdered with a mesh size of 200 and smaller. The carbon did not have extremely good wetting qualities, but once it was put into suspension, it did not settle out if it was agitated.

LIST OF SYMBOLS

A = cross sectional area of column, 12.56 $in.^2$

a = interfacial area, $ft.^2$

C_1 = constant (correction for partial pressure of water vapor)

C_2 = constant (60000 x 144)

C_3 = constant (454)

C_4 = constant (640.628)

D = diffusivity, $ft.^2$/second

Efficiency = %

G = mass flow rate of gas into column, lb./hr.$ft.^2$

H = Henry's Law constant, atm./mole fraction SO_2

J = rate of absorption of SO_2, grams/minute

k = mass transfer coefficient, mole/hr.$ft.^2$(change in driving force)

L = liquid rate, cc/minute

M.W. = molecular weight

N = moles

P = total pressure on system, atmospheres

R = gas constant, 82.06 cc.atm./g-mole $^oK.$

S = mass of SO_2 in gas, grams/minute

T = temperature, $^oF.$

t = time, seconds

V = volume flow of gas, liters/minute

x = mole fraction SO_2 in liquid

x^* = equilibrium mole fraction SO_2 in liquid

y = mole fraction SO_2 in gas

y^* = equilibrium mole fraction SO_2 in gas

Subscripts

g = gas phase

i = into column

l = liquid phase

lc = liquid cycle

o = out of column

v = vapor phase

vc = vapor cycle

Greek Symbols

Φ = fraction of liquid on plate changed per cycle

π = constant 3.14159

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